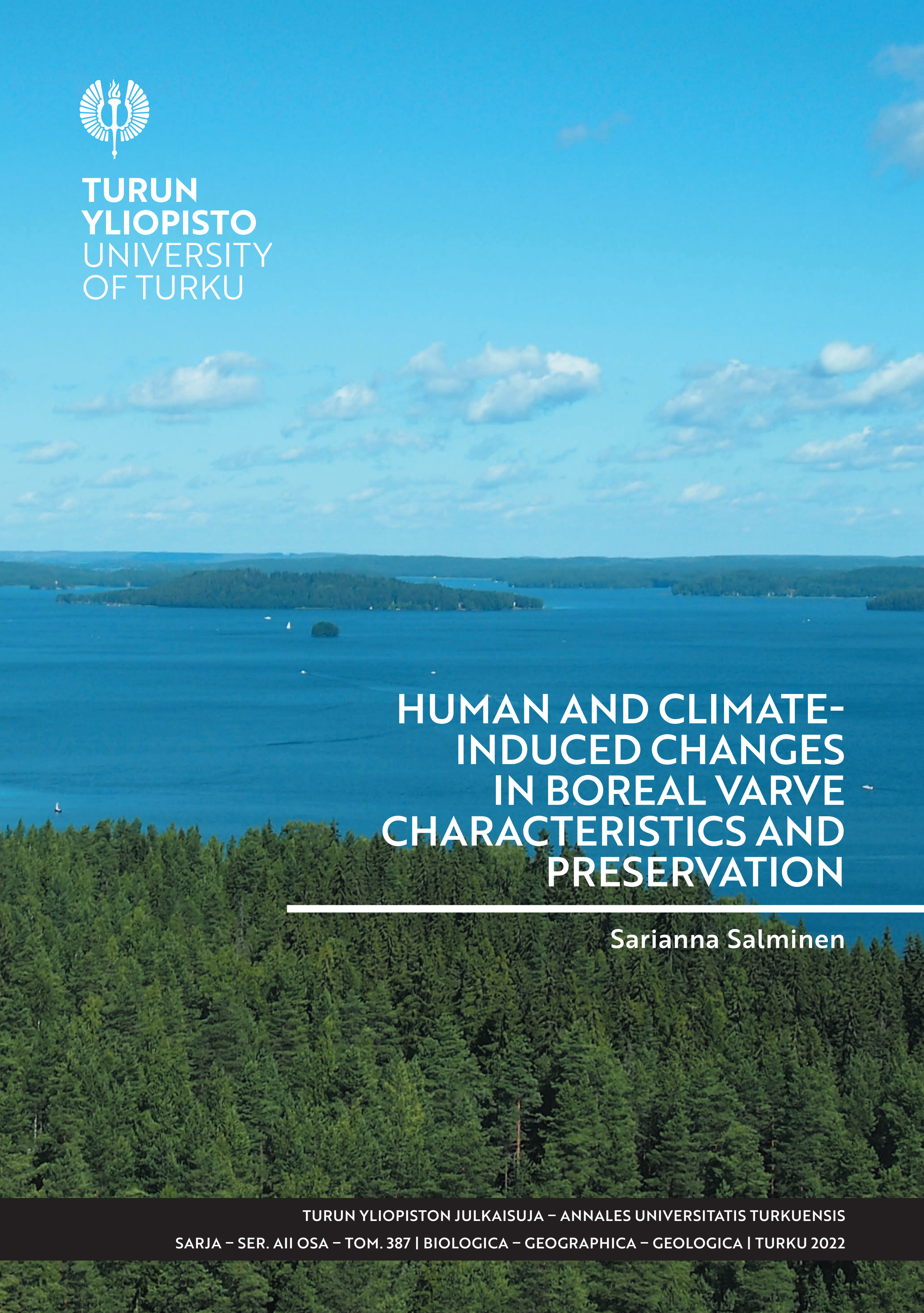

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Sarianna Salminen

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SARIANNA SALMINEN: Human and Climate-induced Changes in Boreal Varve Characteristics and Preservation
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ABSTRACT

Recent variations in varve preservation and characteristics were recorded from Lakes Lehmilampi, Vesijärvi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi to examine how varve formation, preservation, and characteristics respond to climate and anthropogenic actions. From each lake, long cores and freeze corer samples were recovered for varve, elemental, and diatom analysis. The cores were preserved with epoxy embedding to study varve properties, such as varve thickness and varve microfacies with stereomicroscope, petrographic microscope, and X-ray radiography analysis. In the sediments of Lakes Lehmilampi and Vesijärvi, diatom identification and counting were performed from diatom slides prepared using standard procedures. A diatom-total phosphorous transfer function was applied to reconstruct diatom-inferred total phosphorus for diatom samples. In addition to diatom analysis, µXRF analysis was performed on Lake Vesijärvi sediments. Statistical analyses were conducted on Lake Lehmilampi varve parameters and climate parameters to study the factors controlling variations in the extent of varve preservation. Biogenic lamina thicknesses of Lakes Lehmilampi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi were compared to climate parameters to evaluate the response of biogenic lamina thicknesses to variations in climate. The results show that the spatial extent of varves and corresponding hypoxia volume varied during the last 200 years in Lake Lehmilampi. The variation seems to be sensitive especially to winter and March temperatures, autumn and October precipitation as well as November temperature and the number of days with snow cover. Varve and diatom analysis suggest that these variations are more likely related to climatic than anthropogenic forcing. The onset of varve preservation in Lake Vesijärvi occurred first at the deepest point of the Enonsaari Deep in the late 1930s due to cultural eutrophication and subsequently proceeded to shallower depths. Varve preservation weakened and varve characteristics changed as a result of rehabilitation actions. Lake aeration had the single most notable impact on varve preservation as it finally terminated it. Moreover, aeration-induced turbulence transformed the accumulation zone in the vicinity of the aerator into a transport or an erosional zone. Biogenic lamina thicknesses in Lakes Lehmilampi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi were observed to respond to changes in climate during the last 100 years despite anthropogenic influence. Growing season temperature and open water season precipitation control biogenic lamina thickness, which is thus potential for climate reconstructions.

KEYWORDS: Varve preservation, varve characteristics, hypoxia, climate signal, hypolimnetic hypoxia oscillation, cultural eutrophication, lake restoration, biogenic lamina

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TIIVISTELMÄ

Suomalaisten järvien pohjakerrostumien avulla selvitettiin, miten järvet reagoivat ilmaston ja ihmistoiminnan muutoksiin. Ilmaston ja ihmistoiminnan vaikutusta tutkittiin pohjakerrostumien vuosilustorakenteiden muodostumisen, säilymisen ja ominaisuuksien avulla. Tutkimuksen kohteena olivat Lehmilammen, Vesijärven, Kallio-Kourujärven, Kanteleen, Kuninkaisenlammen ja Linnanlammen pohjakerrostumat. Järvistä kairattiin sekä pitkiä kairanäytteitä että jääsorminäytteitä, joista tehtiin lusto-, alkuaine-, ja piileväanalyysejä. Näytteet imeytettiin epoksiin lustojen ominaisuuksien kuten lustonpaksuuden ja lustojen mikrorakenteiden tutkimusta varten. Näitä ominaisuuksia tutkittiin stereomikroskoopin, petrografisen mikroskoopin ja röntgenkuvien avulla. Lehmilammen ja Vesijärven pohjakerrostumista tunnistettiin piilevät standardimenettelytavan mukaan. Vesijärven pohjakerrostumista mitattiin lisäksi alkuainepitoisuuksia µXRF:llä. Piileväsiirtofunktiota käytettiin piilevien avulla laskettavan kokonaisfosforin laskemiseksi. Lehmilammen lustojen säilyvyyden spatiotemporaaliseen vaihteluun vaikuttavia ilmastoparametrejä tutkittiin tilastollisien menetelmien avulla. Lisäksi Lehmilammen, Kallio-Kourujärven, Kanteleen, Kuninkaisenlammen ja Linnanlammen lustojen biogeenisen lustonosan paksuuden vastetta ilmastoparametrien muutoksiin tutkittiin tilastollisesti. Tulosten perusteella Lehmilammen lustojen säilyvyyden laajuus ja laajuutta vastaava hapettomien vesien tilavuus ovat vaihdelleet viimeisten 200 vuoden aikana. Laajuuteen on vaikuttanut erityisesti talven ja maaliskuun lämpötila, syksyn ja lokakuun sadanta, sekä marraskuun lämpötila ja lumipeitteen kesto. Lusto- ja piileväanalyysit viittaavat siihen, että Lehmilammen lustojen säilyvyyden laajuus on ennemminkin riippuvainen ilmastosta kuin ihmistoiminnasta. Vesijärvessä lustojen säilyminen alkoi ihmistoiminnan seurauksena Enonsaaren syvänteen syvimmässä osassa 1930-luvun lopussa, ja eteni tämän jälkeen syvänteen matalampiin osiin. Kunnostustoimenpiteiden vaikutuksesta lustojen säilyminen heikentyi ja lustojen ominaisuudet muuttuivat. Järven hapettamisella oli suurin yksittäinen vaikutus lustojen säilymiseen, sillä se johti lustojen säilymisen loppumiseen. Hapettimesta aiheutunut turbulenssi muutti hapettimen läheisyydessä sijainneet kerrostumisalueet transportaatio- tai eroosioalueiksi, jolloin lustonmuodostus loppui. Lehmilammen, Kallio-Kourujärven, Kanteleen, Kuninkaisenlammen ja Linnanlammen biogeenisen lustonosan paksuus on ollut riippuvainen ilmastoparametrien muutoksista viimeisten sadan vuoden aikana huolimatta valuma-alueella tapahtuneesta ihmistoiminnasta. Kasvukauden lämpötila ja jäättömän kauden sateisuus ohjaavat biogeenisen lustonosan paksuutta, mikä mahdollistaa biogeenisen lustonosan paksuuden käytön ilmastorekonstruktioissa.

ASIASANAT: Lustonmuodostus, lustojen ominaisuudet, hapettomuus, ilmastosignaali, hapettoman alusveden laajuuden vaihtelu, rehevöityminen, järvien kunnostus, biogeeninen lustonosa

Table of Contents

Abbreviations

AOM	Amorphous organic material
BP	Before present
BL	Biogenic lamina
CL	Clastic lamina
^{137}Cs	Cesium-137
DI-TP	Diatom-inferred total phosphorus (µg l^{-1})
EC	Electrical conductivity (mS m^{-1})
FC	Freeze core
Fe	Iron
HHO	Hypolimnetic hypoxia oscillation
IPCC	The Intergovernmental Panel on Climate Change
K	Potassium
LL	Lehmilampi
PCA	Principal component analysis
PC1, PC2	First and second principal component
PC	Piston core, long sediment core
P	Precipitation (mm)
P_O	Open water season precipitation (mm)
P	Phosphorus
S	Sulfur
Si	Silicon
T	Temperature (°C)
T_G	Growing season temperature (°C)
TOT	Total varve thickness (mm)
VJ	Vesijärvi
κ	Magnetic susceptibility
ρ	Correlation coefficient Spearman rho
µXRF	Micro-X-ray fluorescence

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Salminen, S., Saarni, S., Tammelin, M., Fukumoto, Y., Saarinen, T. Varve Distribution Reveals Spatiotemporal Hypolimnetic Hypoxia Oscillations During the Past 200 Years in Lake Lehmilampi, Eastern Finland. *Quaternary,* 2019, 2(2), 20.

II Salminen, S., Tammelin, M., Jilbert, T., Fukumoto, Y., Saarni, S. Human actions were responsible for both initiation and termination of varve preservation in Lake Vesijärvi, southern Finland. *Journal of Paleolimnology*, 2021, p. 1–21.

III Salminen, S., Saarni, S., Saarinen, T. Sensitivity of varve biogenic component to climate in Eastern and Central Finland. *Manuscript.*

1 Introduction

1.1 Varves, their formation, and preservation

Varves are annual sediment laminations that can record information on climatic and environmental changes in seasonal resolution. Thus, varves can form important archives that provide a key for studying past changes in climate and environment, but also for understanding how varying climate conditions and human actions can change lake systems. The formation of varves is dependent on certain geological settings as well as seasonal changes (Ojala et al. 2000; Zolitschka et al. 2015). Strong contrast between seasons in boreal vegetation zone, including ice cover, spring flooding, biogenic productivity blooms from spring to autumn, and stratification of water column, is the main cause of rhythmic sedimentation in Finnish lakes (Saarnisto 1986; Ojala et al. 2000). Furthermore, varve preservation is dependent on geological settings that inhibit post-depositional sediment disturbance, such as bioturbation and turbulence-induced sediment mixing (Saarnisto 1986; Ojala et al. 2000; Tylmann et al. 2013; Zolitschka et al. 2015).

Several varve types, such as clastic, biogenic, and clastic-biogenic varves, have been found in boreal environment (Ojala et al. 2000; Hyttinen et al. 2011; Saarni et al. 2017). Of these varve types, clastic-biogenic varves are the most common in boreal lacustrine environment. In clastic-biogenic varves, a single varve unit is composed of i) clastic lamina (CL) and ii) biogenic lamina (BL) (Figure 1). CL represents snow and ice melt inducing spring flooding that transports minerogenic matter into the lake whereas BL consists mainly of biogenic matter produced during the growing season (Zolitschka et al. 2015). Additional CL may be formed due to flooding that results from autumn rainstorms.

Conditions for varve formation and preservation are favorable in Finland for several reasons. First, the seasonal contrast is strong. Secondly, the number of lakes is high (168 000 lakes > 0.05 ha) (Staudinger 2019), and due to their glacial origin, the lakes are relatively deep compared to their surface area. Thus far, multiple varved lakes, in which varve records span thousands of years, have been found in Finland (Ojala 2000; Saarni 2017), the oldest records starting from Early Holocene (Lake Nautajärvi, ~10 000 years; Ojala and Alenius 2005). In addition to this natural tendency for varve preservation, the preservation of varves can be triggered by cultural eutrophication resulting in hypolimnetic hypoxia (Paper II; Jenny et al. 2013; Kienel et al. 2013; Hernández-Almeida et al. 2017) that prevents bioturbation in the lake bottom.

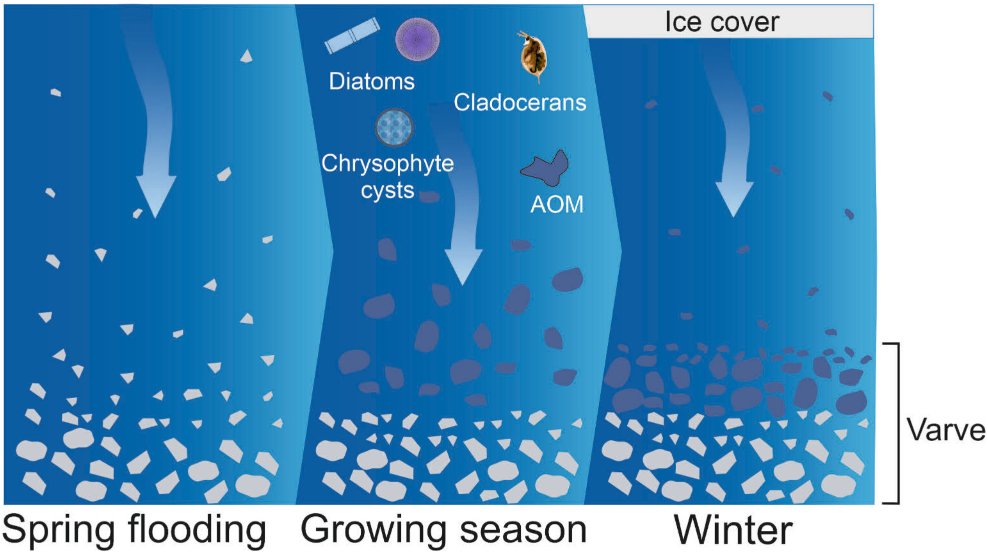

Figure 1. Formation of clastic-biogenic varves in ideal conditions. The clastic lamina (light-colored layer) originates from clastic material transported to the lake during spring flooding following the snow and ice melt. The biogenic lamina (dark-colored layer) consists mostly of autochthonous or allochthonous biogenic material produced in the lake or its catchment during growing season. The biogenic material can consist of, for instance, amorphous organic matter (AOM), plant remnants, micro and macro fossils (i.e., cladoceran remains), and algae (i.e., diatoms). The fine-grained biogenic matter that ends the varve year settles down under ice cover.

1.2 Importance of varve proxies

Dating paleolimnological records is crucial in any paleoenvironmental research. Reliable dating enables temporal comparison of varve parameters and climate or environmental changes. Varve counting of continuous varve records provides a precise dating method. Though additional dating method is required to verify the accuracy of varve counting, the uncertainty of the method can be as low as ~ 1% (Ojala et al. 2012).

The advantage of varve records is that they provide information on seasonal changes in high accuracy and that the variations within different seasons can be studied separately. Annual and seasonal sedimentation rates can be measured from varve seasonal laminae. Moreover, varves record variations in physical, chemical, and biological sediment features and thus, provide a key to apply varve analysis for multiple different uses. Variations in seasonal sedimentation and thus varve formation as well as preservation reflect changes in climate and anthropogenic influence (Figure 2).

Varve records have been proven to be suitable archives for answering multiple research questions within paleoclimate and paleoenvironmental studies. Because high resolution varve records may represent tens of thousands of years (e.g., Lake Holzmaar, Vos et al. 1997; Lake Suigetsu, Ramsey et al. 2012), their significance in paleoclimate and paleoenvironmental research is considerable. For instance, varve records have been used to study or reconstruct past temperatures (e.g. Amann et al. 2017; Zander et al. 2021), precipitation (e.g. Amann et al. 2015; Saarni et al. 2015), human-induced pollution (Meriläinen et al. 2010), paleomagnetic variations (e.g. Haltia-Hovi et al. 2010; Ólafsdóttir et al. 2019), glacial activity (Ohlendorf et al. 1997; Striberger et al. 2011), and wildfire and human-induced fire activity (Gaglioti 2016; Miller et al. 2017; Dietze et al. 2019) successfully. Varves are increasingly used when studying recent, human activity-induced changes in lakes. For instance, varve records have been used to study eutrophication histories (Lotter et al. 1997; Corella et al. 2011; Kienel et al. 2013; Sanchini et al. 2020) and hypolimnetic hypoxia oscillation (Paper I; Jenny et al. 2013).

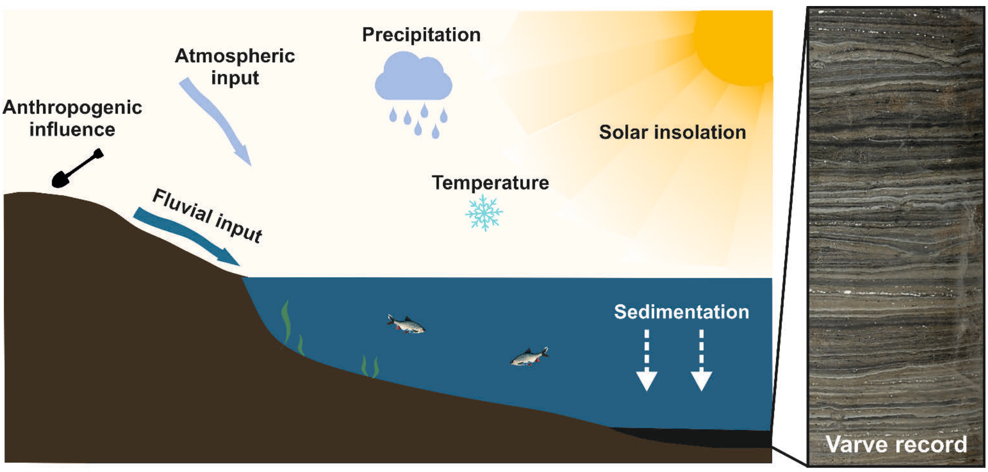

Figure 2. Changes in varve formation, preservation, and characteristics reflect climate (e.g., precipitation, temperature, and solar insolation) and human-induced changes (e.g., cultivation and sewage waters influencing fluvial input).

1.3 Objectives of this thesis

Long varve chronologies have become an important archive to reconstruct past climate conditions (Lücke and Brauer 2004; Martin-Puertas et al. 2017; Kalanke et al. 2020; Bonk et al. 2021). In addition to climate, human-induced changes in the environment influence lake systems (Zolitschka et al. 2015; Jenny et al. 2016 a,b;

Saarni et al. 2017; Lane et al. 2019; Sinyukovich and Chernyshov 2019). Thus, there is a need to better understand how lakes respond to recent changes in anthropogenic activities besides climate.

The principal objective of this study was to evaluate how varve formation, characteristics, and preservation respond to climate and anthropogenic activities during a recent, short time period in lakes with different catchments. To understand the effect of climate and anthropogenic activities on varves, recent (past 80, 100, and 200 years) varve records were compared with meteorological, hydrological, and historical data.

Varve formation, characteristics, and preservation can vary both temporally and spatially (Papers I and II, Jenny et al. 2013), the latter being a previously unexplored aspect in Finnish varve studies. One of the purposes was to investigate, how varve preservation varies through time in respect of basin bathymetry (Paper I), and what drives these spatiotemporal variations in varve preservation and corresponding hypoxia volume (Paper I). The influence of climate, cultural eutrophication, and subsequent rehabilitation actions on varve formation, characteristics, and preservation spatiotemporally, was one of the key study interests (Papers I and II).

Finally, the objective was to investigate the climatic forcing on biogenic lamina and examine the potential of biogenic lamina for paleoclimatic reconstructions (Paper III).

2 Study sites

The study site includes six varve-preserving lakes in Eastern, Central, and Southern Finland (Figures 3,4, Table 1). The lakes are small (surface area 0.05–0.17 km^2) and remote except for the larger Lake Vesijärvi (surface area 107.5 km^2) that is located next to the city of Lahti.

2.1 Lake Lehmilampi

Lake Lehmilampi in the municipality of Nurmes, is a headwater lake with two basins: the northern basin (maximum depth 10.8 m) and the southern basin (maximum depth 11.6 m). The lake has two inflows (one from the southwest and one from the southeast) and one outflow to the northwest. In Lake Lehmilampi, clastic-biogenic varves have preserved since at least approximately 5100 BP (Haltia-Hovi et al. 2007).

2.2 Lake Vesijärvi

Lake Vesijärvi is located between the First and the Second Salpausselkä ice-marginal formations in the vicinity of the city of Lahti in Southern Finland. The lake has several basins of which the Kajaanselkä basin is deepest (42.0 m). The lake has several inflows and is impacted by groundwater seepage through the Salpausselkä formations. The preservation of clastic-biogenic varves in the lake begun in the 1930s (Paper II).

Lake Vesijärvi, especially the Enonselkä Basin next to the city of Lahti (Figure 4), has suffered from eutrophication since the early 20th century culminating in the 1960s and 1970s (Keto 1982; Keto and Sammalkorpi 1988; Liukkonen et al. 1997; Kairesalo and Vakkilainen 2004). Since the 1970s, the lake has been subject to rehabilitation actions, such as diversion of waste water into a water treatment facility, biomanipulation, and lake aeration (Keto 1982; Keto and Sammalkorpi 1988; Salmi et al. 2014). The rehabilitation trajectory continues today.

2.3 Lake Kallio-Kourujärvi

Lake Kallio-Kourujärvi is located in the municipality of Suonenjoki and has three inflows, two from the south and one from the west, and one outflow to the north. Contrary to other studied lakes, varve type in Lake Kallio-Kourujärvi is biogenic (Saarni 2017). The preservation of varves initiated over 3000 years ago (Saarni 2017). Lake Kallio-Kourujärvi is oligotrophic (HERTTA database), unlike the other study lakes.

2.4 Lake Kantele

Lake Kantele locates in Kiuruvesi municipality and has three inflows, two from the north and one from the southwest, and one outflow to the east. The sediment in Lake Kuninkaisenlampi is clastic-biogenic and forms a varve record spanning thousands of years (Saarni 2017).

2.5 Lake Kuninkaisenlampi

Lake Kuninkaisenlampi is located in the area of the city of Kuopio. Lake Kuninkaisenlampi has one inflow from the southeast and is connected by a narrow channel to adjacent Lake Muuruvesi, a part of the larger Lake Kallavesi. Clastic-biogenic varve record of Lake Kuninkaisenlampi spans more than 3600 of years back in time (Saarni et al. 2016).

2.6 Lake Linnanlampi

Lake Linnanlampi is situated in the area of the city of Kuopio and has two inflows, one from the south and one from the north, and one outflow to the east. The catchment area of Lake Linnanlampi is large compared to its surface area. The lake is characterized by clastic-biogenic varve type whose preservation started thousands of years ago (Saarni 2017).

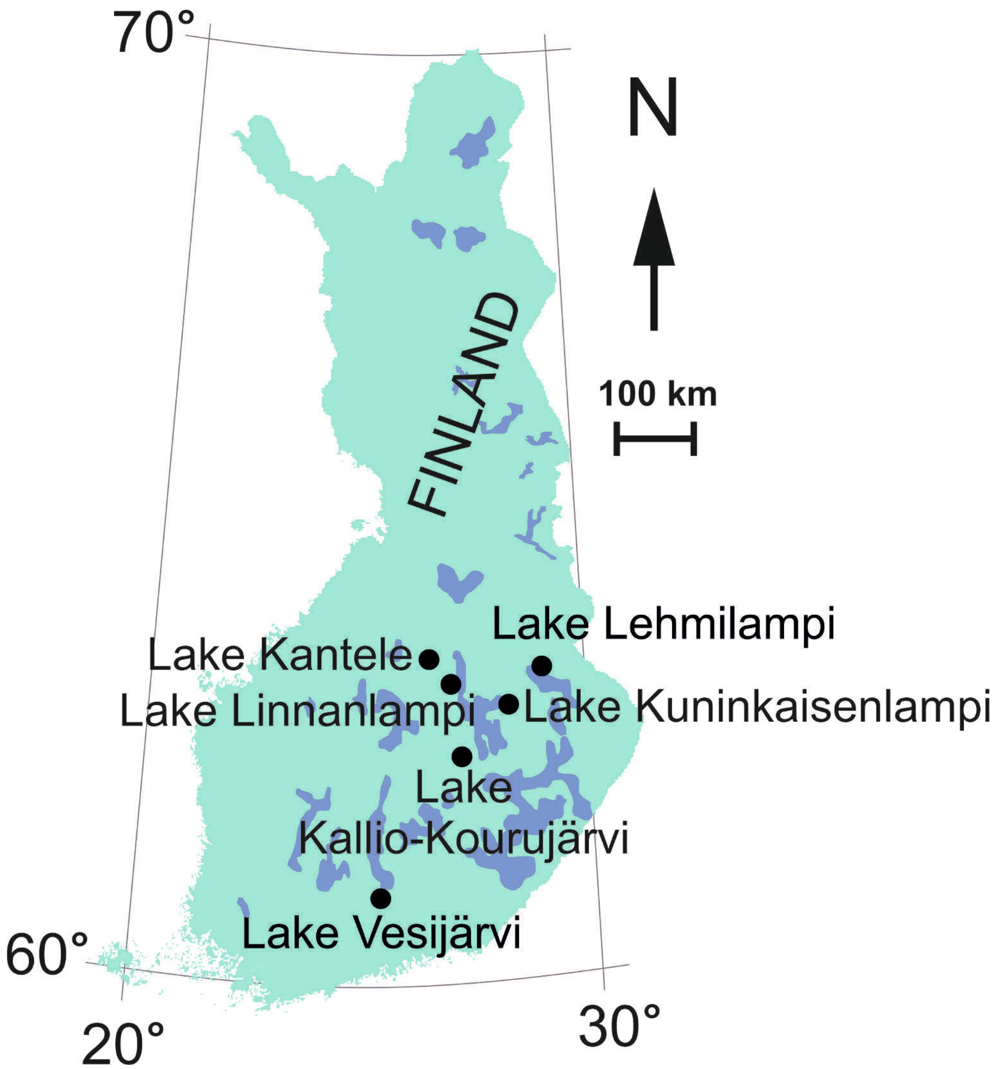

Figure 3. Locations of the studied lakes in Finland

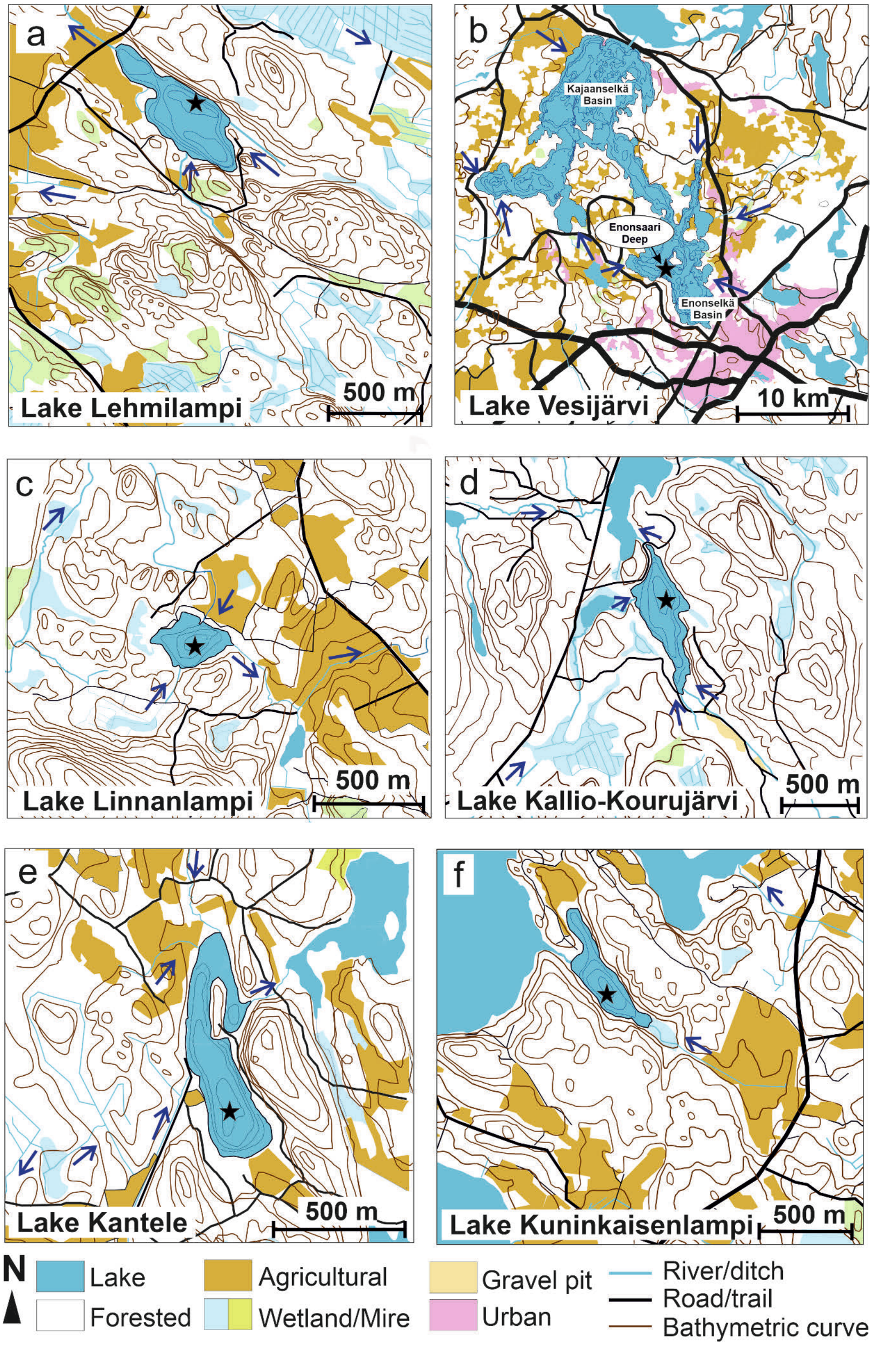

Figure 4. Studied lakes, their nearby catchment, and sampling points. Sampling points are marked with stars and flow directions are marked with blue arrows.

Table 1. Details of the studied lakes (Maankamara database; HERTTA database).

	Lake Lehmilampi	Lake Vesijärvi	Lake Kallio-Kourujärvi	Lake Kantele	Lake Kuninkaisen-lampi	Lake Linnanlampi
Location coordinates	63°37'N, 29°06'E	61°01'N, 25°05'E	62°34'N, 27°01'E	63°29'N, 26°39'E	62°58'N, 28°14'E	63°19'N, 27°10'E
Surface area (km^2)	0.17	107.5	0.13	0.1	0.05	0.05
Catchment area (km^2)	1.0	515.0	10.0	1.0	1.1	9.0
Maximum water depth (m)	11.6	42.0	11.0	12.0	10.1	11.0
Main surface deposits in the catchment	Sandy till, silt, and clay.	Clay and fine to coarse sand.	Mixed soil type or sandy till, lots of outcrops	Mixed soil type	Mixed soil type, fine-grained soil type	Fine grained till
Trophic status and additional information	Eutrophic, Headwater lake	Eutrophic, Located between Salpausselkä ice-marginal formations.	Oligotrophic	Eutrophic	Eutrophic	Eutrophic

2.7 Climate in the study area

The study area is located in boreal climate zone featured with high seasonal temperature contrasts. In Kuopio meteorological station area, 107, 50, 84, 31, and 56 km from Lakes Lehmilampi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi, respectively, the climate is characterized by cold winters and mild summers (FMI database) (Table 2). The climate in Lahti Sopenkorpi meteorological station area, 1.5 km from Lake Vesijärvi, is characterized by slightly milder winters and warmer summers (FMI database) (Table 2).

Table 2. Mean seasonal temperatures (T) and precipitation (P) in Kuopio and Lahti Sopenkorpi meteorological stations based on the data for the past 30 years (FMI database). Also, ice cover duration, and timing of spring and autumn overturns in Kuopio and Lahti areas are given (Korhonen 2005; HERTTA). Spring refers to March-May, summer to June-August, autumn to September-November, and winter to December-February periods.

Climate variable	Kuopio meteorological station / area	Lahti Sopenkorpi meteorological station / area
T_{annual} (°C)	3.2	4.4
T_{spring} (°C)	2.2	3.5
T_{summer} (°C)	15.2	15.5
T_{autumn} (°C)	3.7	4.6
T_{winter} (°C)	-8.5	-6.0
P_{annual} (mm)	626.0	653.0
P_{spring} (mm)	111.0	108.0
P_{summer} (mm)	222.0	221.0
P_{autumn} (mm)	161.0	181.0
P_{winter} (mm)	132.0	136.0
Ice cover duration (d)	90–210	80–210
Start of spring overturn period (i.e., start of destratification)	May	April–May
Start of autumn overturn period (i.e., start of destratification)	September–October	August–October

3 Materials and Methods

3.1 Sediment sampling

The cores from Lake Lehmilampi and Lake Vesijärvi were obtained from the lake ice cover in spring 2014 and 2018, respectively. The cores from Lake Kallio-Kourujärvi were recovered in spring 2008 and from Lakes Kantele, Kuninkaisenlampi, and Linnanlampi in spring 2009 during a previous research project (Saarni et al. 2015, 2017; Saarni 2017). In Lake Lehmilampi, the cores were recovered along two water-depth transects (from 6.5 to 10.8 m water depths) that both begun from the deepest point, 10.8 m, of the northern basin (Figure 4). In Lake Vesijärvi, the cores were obtained from a water-depth transect (from 23.8 to 32.0 m water depths) that crossed the location of an aerator at the deepest point, 32.0 m, of the Enonsaari Deep (Figure 4). In Lakes Kantele, Kuninkaisenlampi, and Linnanlampi, the cores were recovered from the deepest point of the lake (Figure 4). The long sediment cores were taken with a Livingston-type piston corer. The freeze-corer samples were taken from the HTH corer (Renberg and Hansson 2008) sample using the ice-finger technique (Saarinen and Wenho 2005). In this technique, a hollow aluminium wedge is pushed into the sample that is contained in the HTH corer tube. The aluminium wedge is filled with dry ice to obtain an undisturbed, frozen sediment surface sample along the outer surface of the wedge.

3.2 Magnetic susceptibility

Magnetic susceptibility (κ) measurements were performed on fresh and cleaned sediment surface of the lengthwise halved long sediment cores of Lake Lehmilampi. A Bartington MS2 susceptibility meter connected to a Bartington MS2E core logging sensor was used for magnetic susceptibility analysis. The measurements were made at 2 mm intervals on an automatic measuring track.

3.3 Sediment treatments

The freeze-corer samples from Lake Lehmilampi were cut to approximately 13 cm long sub-samples with 2.0 cm overlap. The long sediment cores of Lakes Vesijärvi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi, were split lengthwise into two halves and 11-cm-long sub-samples with 1.5 cm overlap were taken from one of the core halves. The epoxy embedding of Lakes Lehmilampi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi was performed using water-acetone-epoxy exchange method (Lamoureux 1994; Tiljander et al. 2002) where the water in the samples was first replaced with acetone and then the acetone was replaced with Spurr low-viscosity epoxy resin. For the sub-samples of Lake Vesijärvi, shock-freeze and freeze-dry technique (Lotter and Lemcke 1999) was used. In this technique, the sub-samples were first shock-frozen with liquid nitrogen and then dried with a Christ laboratory freeze dryer to remove all the water from the sediment. Finally, the sub-samples were embedded in Araldite epoxy.

The embedded sub-samples of Lakes Lehmilampi and Vesijärvi were sawn and polished into 1.8-mm slabs for X-ray radiography and µXRF analysis, respectively. For microscopy analysis, 30–50-µm thin sections were prepared from the embedded sub-samples with an ASTERA CUT8 diamond saw and an ASTERA GRN16 grinder to study sediment microstructure. Thin sections of the sediments from Lakes Lehmilampi and Vesijärvi were prepared at the Geology section at the University of Turku. Thin sections of Lakes Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi had been prepared earlier during previous research project (Saarni et al. 2015, 2017; Saarni 2017).

3.4 X-ray radiography and µXRF analysis

The µCT scanner Nanotom 180 NF at the Department of Physics of the University of Helsinki was used for X-ray radiography of the embedded 1.8-mm Lake Lehmilampi sub-samples. For the embedded 1.8 mm sub-samples of Lake Vesijärvi, the µXRF analysis was performed at the Geology section of the University of Turku with a vacuum-operated Bruker Tornado µXRF analyzer (tube current 600 µA, 50 kV, distance of pixels 60 µm, spot size 20 µm, Rhodium anode). The µXRF data was examined in the Esprit M4 software using continuous series of multi-element line scans (single line, width 9 pixels) and 2D elemental maps.

3.5 Microfacies analysis and varve chronology

Varve microfacies was determined from thin sections of Lakes Vesijärvi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi with a Leitz Laborlux petrographic microscope coupled with a Euromex HD-Ultra camera. Varve and lamina thicknesses were measured, varve counting was performed, and detailed observations on the occurrence of clastic and biogenic components were made. For Lake Lehmilampi, the varve and lamina thicknesses were measured from the X-ray radiographs and embedded and polished 1.8 mm sub-samples. The polished sub-samples were analyzed with a Canon EOS 600D camera and Canon EOS Utility software coupled with a Nikon SMZ800 stereomicroscope.

Error estimates for each varve chronology were calculated using the approach by Lotter and Lemcke (1999). Each varve sequence was counted three times and the mean of the three counts was used to calculate the error estimates, i.e. ±X% difference of the count minimum and maximum versus the count mean.

3.6 Dating

Varve counting was used to date each sediment sequence. To verify the varve counting-based dating, ^{137}Cs activities from sediments of Lakes Lehmilampi, Vesijärvi, Kantele, and Linnanlampi were measured at the Geological Survey of Finland. Activities were measured using a BrightSpec gamma spectrometer (3600 s counting time) from a continuous series of fresh sub-samples, representing 1–7 varve years. The major peak in ^{137}Cs activity was considered to represent year 1986, the year of Chernobyl nuclear accident. The minor peak was considered most likely to represent atmospheric nuclear tests in 1963. The cores from the sampling transect within a lake (Lakes Lehmilampi and Vesijärvi) were dated by correlating them visually (marker horizons), chemically (µXRF profiles), or physically (magnetic susceptibility profiles) with fully dated and varved sediment cores that were obtained from the deepest point of the lake. Some of the cores from Lakes Lehmilampi and Vesijärvi contained non-varved sediment sections. These non-varved sections were dated by comparing and correlating the varved sections below or above the non-varved sections with the dated and fully varved sediment cores.

3.7 Diatom analysis

Diatom slides were prepared from fresh sediment sub-samples of Lakes Lehmilampi and Vesijärvi using standard procedures by Battarbee et al. (2001). For Lake Lehmilampi, the diatoms slides were prepared from altogether 15 fresh sub-samples (volume approximately 5 cm^3). Each diatom slide represents one of the seven hypoxia or one of the six baseline periods that were determined based on the microfacies analysis. Because three sub-samples from the longest, two from the second longest and none from the shortest hypoxia period were recovered, altogether nine and six fresh sediment sub-samples were recovered from hypoxia and baseline periods, respectively. In Lake Vesijärvi sediment, diatom slides were prepared from a continuous series of 41 fresh sediment sub-samples (volume 2 cm^3) that were taken at 4 cm intervals. At least 300 diatom valves were identified from each slide to species level under an optical microscope (x1000 magnification). The identification was conducted using the taxonomical references of Krammer and Lange-Bertalot (1986, 1988, 1991a,b) and the updated nomenclature of Porter (2008), Spaulding et al. (2008) and Guiry and Guiry (2018). For plotting the diatom stratigraphy, TILIA and TILIAGRAPH software (Grimm 1991) were used.

3.8 Hydrological, meteorological, and GIS data

Hydrological monitoring data were uploaded from HERTTA database maintained by Finnish Environment Institute. The meteorological data were uploaded from NORDKLIM Dataset (Dataset for Climate Analysis with Data from the Nordic Region). Geographical Information Systems (GIS) data were uploaded from Finnish Environment Institute database (FEI 2018), Maankamara Digital map database and Hakku database maintained by the Geological Survey of Finland, as well as Paituli Spatial Data Download Service and Topographic Database maintained by National Land Survey of Finland.

3.9 Statistical analyses

When comparing varve parameters of Lakes Lehmilampi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi with meteorological data, correlations between variables were counted with the software R3.4.3 (R Development Core Team). The Kolmogorov-Smirnov normality test was applied to test the normality of data. Spearman's Rank Correlation analysis was used because in each case either of the variables was not normally distributed.

To minimize the effect of possible inaccuracies in varve counting and to regard decadal trends in climate data, running means were used. For the hypoxia volume of Lake Lehmilampi and compared climate data, 10-year running mean was used (Paper I). For BL thicknesses of Lakes Lehmilampi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi and compared climate data, 11-year running mean of variables was used (Paper III). Diatom assemblage changes were investigated with principal component analysis (PCA) using Canoco 4.5 for Windows (Ter Braak and Šmilauer 2002). Diatom-inferred total phosphorus (DI-TP) was reconstructed from diatom samples by applying the diatom-TP transfer function of Tammelin et al. (2017) in C2 software (version 1.6.8).

4 Results

4.1 Review of papers I-III

4.1.1 Paper I: Salminen, S., Saarni, S., Tammelin, M., Fukumoto, Y., Saarinen, T. Varve Distribution Reveals Spatiotemporal Hypolimnetic Hypoxia Oscillations During the Past 200 Years in Lake Lehmilampi, Eastern Finland

In this paper, varve records from two water-depth transects were used to reconstruct spatiotemporal changes in varve preservation during the past 200 years. Hypolimnetic hypoxia (oxygen level ≤ 2 mg L^{-1}) (Diaz 2001) is essential for varve preservation and hence hypolimnetic hypoxia oscillation (HHO) during the studied period were reconstructed using varve preservation as a proxy. Two analyses were used to identify the changes in varve preservation: varve analysis from (1) the epoxy-embedded sub-samples and (2) X-ray radiographs. The spatial distribution of varve preservation area and the water volume (hypolimnetic hypoxia volume) corresponding to this area were determined in the ArcGIS ArcMap 10.1 software. Measurement data from the National Land Survey of Finland (NLS) and water depth measurements during sampling were used to interpolate the bathymetric contours of Lake Lehmilampi. The relationship between HHO and climatic factors (NORDKLIM dataset) were evaluated. The relation of hypoxic periods to cultural eutrophication was estimated by analyzing changes in diatom assemblages.

Results show that hypoxia volume (percentage of lake water volume corresponding to varve preservation of the whole lake volume) varied during the previous 200 years (Figure 5), and seven periods of extensive hypoxia were identified within this timeframe. The outcome of this study is that HHO in Lake Lehmilampi is more likely related to climate rather than human influence.

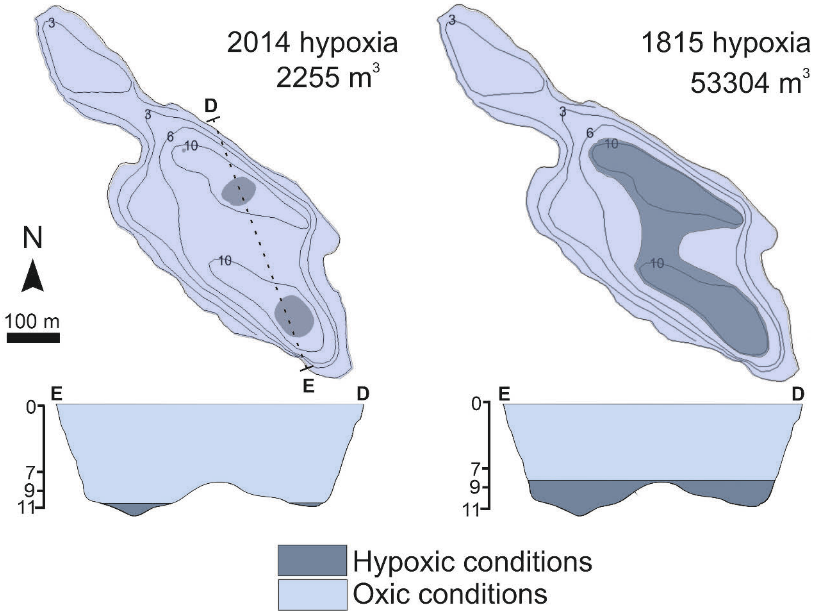

Figure 5. Varve preserving areas corresponding to hypoxic water volume (m^3) in 2014 and 1815 in Lake Lehmilampi. Dashed line DE shows the location of bathymetric cross-sections. Hypoxic conditions are indicated in darker colour and oxic in lighter colour.

4.1.2 Paper II: Salminen, S., Tammelin, M., Jilbert, T., Fukumoto, Y., Saarni, S. Human actions were responsible for both initiation and termination of varve preservation in Lake Vesijärvi, southern Finland

This paper shows how human influence and rehabilitation actions have affected varve preservation in the Enonsaari Deep of Lake Vesijärvi during the past 80 years. Varve microfacies, elemental, and diatom analyses were applied to reconstruct the changes in varve preservation, varve characteristics, and diatom assemblages. Long sediment cores and freeze corer samples were recovered from a water-depth transect crossing the deepest point of the deep at the location of an aerator.

Four sediment types were identified: varve type I, varve type II, poorly varved, and non-varved type (Figure 6). Varve types I and II consist of two laminae: CL and BL (Figure 6a). BL in varve type I consists of three sub-laminae: BL-a, BL-b, and BL-c, whereas in varve type II the BL consists only of BL-a and BL-b. The mean varve thickness at the deepest point of the basin is 1.9 cm. *Stephanodiscus parvus* Stoermer and Håkansson is the most dominant taxon of the studied period while *Aulacoseira islandica* forms the majority of areal biomass in BL-b (Figure 6b).

The onset of varve preservation occurred first in the deepest point of the deep proceeding subsequently to shallower depths. Varve preservation reached the largest spatial extent in the 1970s and concomitantly, the most distinguishable varves were formed. Thereafter the spatial extent of varves decreased, and varves gradually weakened until varve preservation was fully terminated in the 2010s. However, the termination was abrupt in the core from the deepest point of the deep, as opposed to the gradual termination in the other cores, likely due to enhanced turbulence caused by the aerator.

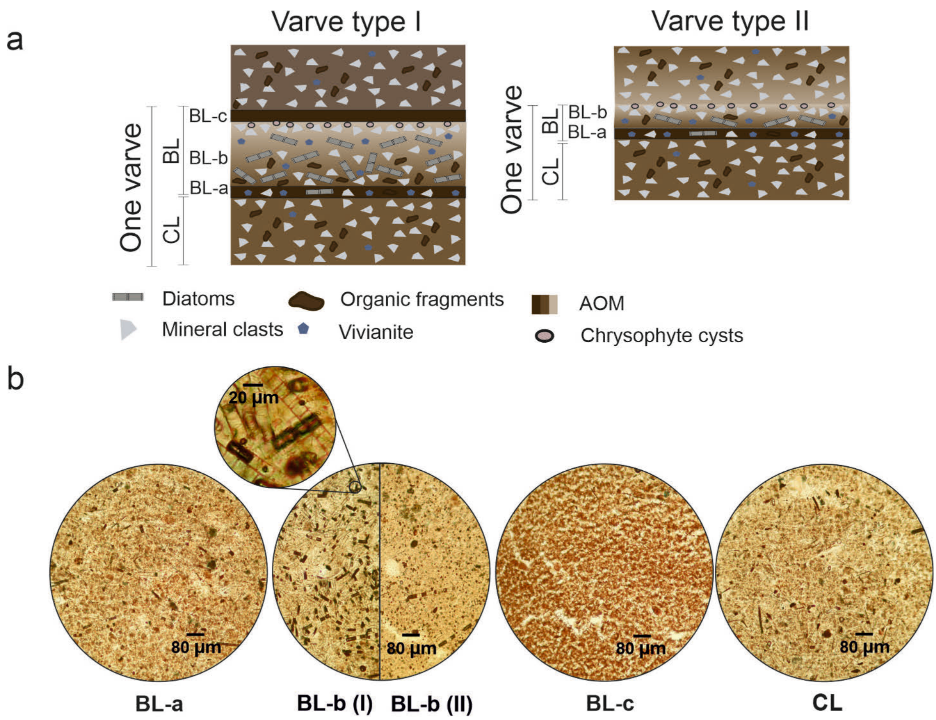

Figure 6. Varve types and their characteristics in the Enonsaari Deep sediments of Lake Vesijärvi. (a) Varve types I and II on laminal and sub-laminal scale. A schematic drawing of clastic (CL) and biogenic laminae (BL) is shown. (b) Microscopy images of sub-laminae in varve types I and II.

4.1.3 Paper III: Salminen, S., Saarni, S., Saarinen, T. Sensitivity of varve biogenic component to climate in Eastern and Central Finland

This manuscript discusses the variations in BL thicknesses and their response to climate and anthropogenic activities in five Finnish lakes: Lehmilampi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi during the past approximately 100 years. Variations in BL thicknesses were compared with growing season (from April to September, mean daily temperature above 5.0 °C, FMI) temperature (T) and open water season (from April to November, FMI) precipitation (P) that were downloaded from NORDKLIM dataset.

During the studied period, significant and insignificant correlations were found during the whole study period (1896–1992 for T and 1895–1992 for P) (Table 3). Generally, BL thickness correlates positively with T and P. The statistically significant positive correlation between these variables suggest that growing season temperature and open water season precipitation control the BL thickness. Lakes Kallio-Kourujärvi and Kantele are exceptions. Lake Kallio-Kourujärvi shows negative correlation between T and BL thickness (Table 3b). Negative correlations are also observed between P and BL thickness in the records of Lakes Kallio-Kourujärvi and Kantele (Table 3).

According to satellite images and old maps (Paikkatietoikkuna database; NLS database), human activities, such as forest cutting and mire dredging, have taken place in the catchments of the studied lakes during the study period. Despite these activities, some climate signal is observed.

Table 3. Correlations between studied climate variables (T and P) and BL. Correlation coefficients (ρ) and p-values for growing season temperature (T_G) and precipitation (P_O) for the whole study period (a) and for short time periods of Lakes Kantele and Kallio-Kourujärvi records (b). Statistically significant correlations are bolded.

a

	Lake Lehmilampi		Lake Kallio-Kourujärvi		Lake Kantele		Lake Kuninkaisenlampi		Lake Linnanlampi	
	ρ	*p*-value	ρ	*p*-value	ρ	*p*-value	ρ	*p*-value	ρ	*p*-value
T_G	**0.52**	**< 0.01**	0.06	> 0.05	**0.74**	**< 0.01**	**0.44**	**< 0.01**	**0.59**	**< 0.01**
P_O	**0.71**	**< 0.01**	-0.12	> 0.05	-0.17	> 0.05	**0.37**	**< 0.01**	**0.32**	**< 0.01**
years	1896–1992 (T_G) 1895–1995 (P_O)		1896–1992 (T_G) 1895–1992 (P_O)		1896–1992 (T_G) 1895–1992 (P_O)		1896–1992 (T_G) 1895–1992 (P_O)		1896–1992 (T_G) 1895–1992 (P_O)	

b

Lake Kallio-Kourujärvi			
Period	Variable	ρ	*p*-value
1896–1973	P_O	**-0,34**	**< 0.01**
1979–1995	P_O	**0.71**	**< 0.01**
1896–1936	T_G	**0.43**	**< 0.01**
1937–1992	T_G	**-0.36**	**< 0.05**

Lake Kantele			
Period	Variable	ρ	*p*-value
1896–1966	P_O	**-0.34**	**< 0.01**
1975–1995	P_O	**-0.52**	**< 0.05**

5 Discussion

5.1 Climate forcing on varve formation and preservation

5.1.1 Biogenic lamina thickness and climate

The biogenic matter in lake sediments originates from autochthonous primary production in the lake and allochthonous sources (Meyers and Lallier-Vergés 1999). Autochthonous primary production is dependent mainly on nutrient and light availability and lake water temperature (Kimmel and Groeger 1984; Kelly et al. 2018). Allochthonous influx is controlled by allochthonous production and transportation ultimately depending on a mixture of several factors, such as precipitation, air temperature, vegetation, and surface deposit type of catchment as well as catchment morphology (Cohen 2003; Hanson et al. 2014; Zolitschka et al. 2015). In addition to primary production and transport of allochthonous organic matter, biogenic content is also subjected to degradation (Meyers and Lallier-Vergés 1999).

Deposition of the varve biogenic component and its potential for climate reconstructions have been studied and shown to reflect climate and carry great potential for climate reconstructions (Saarni et al. 2015; Sanchini et al. 2020; Zander et al. 2021). BL thicknesses of Lakes Lehmilampi, Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, and Linnanlampi respond to changes in climate variables and the results show that biogenic lamina thicknesses have potential for reconstructing growing season and open water season climate (Paper III). For example, in Lakes Lehmilampi, Kuninkaisenlampi, and Linnanlampi, both T and P generally correlate positively with BL thickness. High BL thicknesses are observed during warm growing season, but also coincide with enhanced precipitation during open water season. Generally, warmer growing season enhance primary production in the lake and its catchment if nutrients are available and can hence lead to thicker BL. Increased primary production is followed by enhanced oxygen demand due to degradation of organic matter, which can lead to oxygen deficiency in the hypolimnion. During warm growing seasons, oxygen deficiency can result also from highly stable and prolonged stratification that prohibits oxygen transfer into hypolimnion (Jankowski et al. 2006; Boehrer and Schultze 2008). Either way, anoxic conditions can enhance the preservation of organic matter and promote phosphorous release from the sediment (Mortimer 1941, 1942; Kamp-Nielsen 1975; Spears et al. 2007) which can later boost primary production. High precipitation can transport increased amounts of nutrients into the lake enhancing autochthonous production, but also transport more allochthonous organic matter to the lake resulting in thicker BL.

However, not every lake responds to variations in climate similarly. Catchment characteristics, lake morphology, and lake elevation, for instance, can determine how lakes respond to climate (Adrian et al. 2009; Hayes et al. 2017). Negative correlation with T and BL thickness in Lake Kallio-Kourujärvi record during 1937–1992 (Paper III, Table 3) could be partly explained by limited nutrient supply in the lake with low trophic state. It is also possible that during high temperatures, production rate in the lake is overridden by enhanced degradation of organic matter leading to negative correlation between T and BL thickness. This is because organic matter degradation already in the water column can be enhanced due to warmer temperatures (Jankowski et al. 2006), if not overridden by the effects of thermal stratification, leading to decreased biogenic lamina thickness. Negative correlations between P and BL thickness (Paper III, Table 3) could also be partly explained by the catchment. Although high oxygen concentration in the water column promotes primary production, it also enhances degradation of organic matter. If oxygen-rich waters with only very limited amounts of nutrients and terrestrial organic matter enter the lake, the production rate could be overridden by enhanced degradation of organic matter.

5.1.2 Varve preservation versus climate

Varve preservation is ultimately dependent on hypoxia that prevents bioturbation (Saarnisto 1986; Ojala et al. 2000; Tylmann et al. 2013; Zolitschka et al. 2015). Hypoxic conditions are most common in the deep waters of hypolimnion and indeed, continuous varve chronologies are usually found at the deepest point of a lake (Ojala 2000; Tiljander 2005; Haltia-Hovi et al. 2007; Haltia-Hovi et al. 2011; Dräger et al. 2017; Bonk et al. 2021). However, the depth of hypolimnetic hypoxia and thus the volume of hypoxic waters in the lake bottom, varies in response to fluctuations in climate (Paper I; Jenny et al. 2013). Climate can affect oxygen availability on the lake bottom via interaction of several factors, such as water temperature, degradation of organic matter, stability of the water column stratification (Straile et al. 2003), and lake level variations (Zolitschka et al. 2015).

In the HHO of Lake Lehmilampi, seven hypoxia periods were identified. The onset of these periods is rapid and intensive, while the return from hypoxia period to baseline oxygen conditions seems to be more gradual (Paper I). These findings of the onset and return of hypoxia periods are in accordance with the previously reported slow responses in hypolimnetic hypoxia to reduced external forcing (Jenny et al. 2016a). The length of hypoxia periods may have been underestimated because bioturbation could have disturbed previous hypoxia-associated varve sequences.

Based on correlation analyses between HHO and climate parameters as well as diatom analysis, climate seems to be a more likely factor rather than human influence for triggering the observed fluctuations in varve preservation and hypolimnetic hypoxia volume in Lake Lehmilampi during the past 200 years (Paper I). The results show that March and winter T correlated positively with hypoxia volume, whereas negative correlations were observed between hypoxia volume and the number of days with snow cover, November T, as well as autumn and October P, (Paper I). These variables may have influenced the hypoxia volume through changes in the intensity water mixing during overturns (Paper I). For instance, variations in P can influence the runoff of well-oxygenated waters entering the lake leading to variations in in the intensity of autumn overturn and oxygen exchange and thus, varve preservation.

Despite human presence in the lake catchment prior to the studied period, no clear signal of cultural eutrophication in HHO was observed. Similarly, as suggested for Lake Lehmilampi, climate-controlled lake circulation is shown to be the factor controlling hypoxia oscillations in Lake Tiefer See (Dräger et al. 2017). Interestingly, Lake Tiefer See shows that hypoxia-control shifted recently from climate to human-induced eutrophication. However, this is not the case with rather remote Lake Lehmilampi.

To conclude, the interaction between the possible forcing factors and variations in varve spatiotemporal preservation and hypoxia seems complex. Thus, further investigation was proposed to understand the role of individual forcing factors in varve preservation and hypoxia in Lake Lehmilampi.

5.2 Anthropogenic influence on varves

5.2.1 Anthropogenic influence on biogenic lamina thickness

Anthropogenic activities can cause alterations in BL thickness and weaken, or even mask, the climate signal (Zolitschka et al. 2003; Paper II). Conversely, anthropogenic activities can amplify the climate signal in certain cases (Itkonen and Salonen 1994; Bush et al. 2017). Anthropogenic activities, such as forest cutting and clearing, mire/bog ditching, and cultivation, can influence the erodibility of the catchment soil (Zolitschka 1998; Saarni et al. 2017; Arnaud et al. 2016). Because of increased erodibility, transportation of biogenic matter and nutrients into the lake enhances. The use of chemical fertilizers can also increase nutrient leaching from the fields into the lake. Generally, anthropogenic factors have been documented to result in an increase in total varve thickness during the 20^{th} century (Itkonen and Salonen 1994; Tiljander et al. 2003; Meriläinen et al. 2010; Saarni et al. 2015).

During the past 100 years, multiple anthropogenic activities have occurred in the catchments of the studied lakes (Papers II, III). Because of ditching, forest cutting, and forest clearance for agricultural purposes in the catchment, the climate signal may have altered (Paper III). Despite the anthropogenic influence, climate signal is detectable in varve chronologies of these remote lakes and thus the varve chronologies have high potential for growing season and open water season climate investigation.

5.2.2 The onset of varve preservation

In all the studied lakes, except Lake Vesijärvi, varve preservation has initiated thousands of years ago (Haltia-Hovi et al. 2007; Saarni et al. 2015, 2016; Saarni 2017), which is common in varve-preserving lakes in Finland (Ojala 2000; Tiljander 2005; Haltia-Hovi et al. 2011). The organic-rich soil type on the catchments of Lakes Kantele, Kuninkaisenlampi, and Linnanlampi favors natural eutrophication (Tammelin et al. 2017; Tammelin and Kauppila 2018) and consequent oxygen depletion. However, in originally non-varved lakes or in lakes with occasional varve sequences, cultural eutrophication can result in varve preservation (Paper II; Lotter et al. 1997; Kienel at al. 2013; Jenny et al. 2013; Rowell at al. 2015; Jenny et al. 2016 a,b).

Indeed, varve preservation through cultural eutrophication and consequent oxygen deficiency is observed in Lake Vesijärvi since 1930s (Paper II). Increased sewage loading enhances autochthonous production and oxygen consumption that can eventually lead to hypoxia (Paper II; Smol 2009; Müller et al. 2012; Friedrich et al. 2014) that gives rise to varve preservation (Paper II; Jenny et al. 2013; Jenny et al. 2016 a,b). In Lake Vesijärvi, the excessive sewage loading and industrial effluent discharge triggered cultural eutrophication and hypoxia as well as varve preservation (Paper II). In addition to oxygen consumption, increased rates of organic matter, as well as industrial chemical compounds, can increase the density of hypolimnion and the density stratification stability of the lake (Hakala 2004; Boehrer and Schultze 2008). Thus, intensified density stratification could have decreased the overturn depth and thus further promoted varve preservation in Lake Vesijärvi (Paper II).

5.2.3 Changes in varve preservation and in varve characteristics

Human-induced changes in the lake and its catchment can enhance, weaken, or even terminate varve preservation (Paper II; Rowell et al. 2015; Dräger et al. 2017; Poraj-Górska et al. 2017). Decreased oxygen availability or increased supply of allochthonous matter can promote varve preservation (Paper II; Ojala et al. 2000; Zolitschka et al. 2015). Alternatively, varve preservation can weaken due to increased oxygen availability and subsequent bioturbation (Paper II; Saarnisto 1986; Ojala et al. 2000; Zolitschka et al. 2015). Additional components or sub-laminae can emerge or fade (Papers II, III). For instance, in Lake Kallio-Kourujärvi, whose varve type was biogenic for thousands of years, occasional clastic laminae started to appear in the topmost varves because of human-induced increase in soil erodibility (Paper III; Saarni et al. 2015). Furthermore, evolving cultural eutrophication in Lake Vesijärvi intensified primary production resulting in emerging of a novel biogenic sub-layer that is nearly completely composed of amorphous organic material (Paper II). The varve and sub-lamina boundaries became more distinguishable also as eutrophication in Lake Vesijärvi intensified (Paper II). Later on, sewage treatment and rehabilitation actions led to disappearance of the aforementioned novel biogenic sub-layer (Paper II).

In the Enonsaari Deep of Lake Vesijärvi, varve preservation and varve characteristics changed spatiotemporally related to the evolving cultural eutrophication and subsequent sewage treatment and rehabilitation actions. This development was to be expected, since varve preservation is dependent on hypoxia, that results from increased primary production and oxygen consumption, as well as sedimentation rate (Zolitschka et al. 2015,) and because varve quality is observed to be dependent on deep-water oxygen conditions (Dräger et al. 2019). In Lake Vesijärvi, that has experienced a wide range of anthropogenic activities, anthropogenic influence has possibly been strong enough to override the climate signal (Paper II).

Lake Vesijärvi varves are thick (mean 19.0 mm) (Paper II) in contrast to the rest of the studied lakes (Papers I, III) and other naturally varve-preserving lakes in Finland (Ojala 2000; Saarni 2017; Czymzik et al. 2018) in which varve thicknesses are typically a few millimeters at most. Similarly as in Lake Vesijärvi, in Lake Tiefer See in the Uckermark (Germany), which has suffered from cultural eutrophication, varve thickness is high, on average 10.1 mm, (Kienel et al. 2013). In Lake Vesijärvi, also the high density of diatoms in BL-b sub-lamina and anthropogenic stress-indicating diatom assemblages of varve type I corresponds to the time of maximum sewage loading in Lake Vesijärvi (Paper II).

Mechanical disturbance of sediments during dredging can generate sediment and nutrient resuspension (Paper II). The resuspension can strengthen the stagnation by increasing density differences in the water column (Hakala 2004; Boehrer and Schultze 2008) and enhance autochthonous production and oxygen consumption through increased organic matter and nutrient influx. Either way, increased sediment and nutrient resuspension can promote varve preservation. Furthermore, high sedimentation rates of clastic material could also result in better varve quality (Ojala et al. 2000). In Lake Vesijärvi, the sediment and nutrient resuspension as a result of the harbor construction in 1964–1965 and dredging in 1990–1991 may have improved varve quality and preservation (Paper II) by causing sediment and nutrient resuspension and thus increased autochthonous production in the lake.

5.2.4 The end of varve preservation

The start of sewage treatment and rehabilitation actions on Lake Vesijärvi led to weakening of varve preservation and disappearance of a biogenic sub-lamina in the Enonsaari Deep (Paper II). This is an expected outcome because the purpose of restoration efforts is to decrease primary production and hypoxia in lakes. However, in the Enonsaari Deep of Lake Vesijärvi, varve preservation did not end at the time of sewage treatment, nor after the biomanipulation or fishery management. This is because phosphorus is released from the deep reactive layer of sediment at anoxic environment despite a significant decrease in external nutrient load and restoration actions (Jilbert et al. 2019). Phosphorus release from sediments delays the lake recovery from eutrophication and thus maintains varve preservation through autochthonous production and consequent higher oxygen demand. Indeed, the legacy of anthropogenic stressors in Lake Vesijärvi is evident today (Salonen et al. 2020) and is emphasized by the diatom assemblages favoring high nutrient levels (Paper II).

A single restoration action can have a notable influence in lake bottom dynamics. In Lake Vesijärvi sediment from the deepest point of the Enonsaari Deep, a strong reduction in sediment accumulation corresponds to the start of aeration (pumping oxygen-rich surface water into hypolimnion). Aeration-induced turbulence can initiate stratification break-up and together with overturn period it can have a significant impact on sediment dynamics and even terminate varve preservation. Indeed, the turbulence resulted in the relocation of the accumulation zone in the Enonsaari Deep and the development of a transport or even erosional zone at least of 45 m distance from the aerator. It is remarkable that human activities cannot only result in such intense cultural eutrophication that promotes varve formation and preservation (Paper II; Rowell et al. 2015; Dräger et al. 2016), but also terminate the formation and preservation when certain restoration action is applied. However, the termination of varve formation and preservation in Lake Vesijärvi is not unique. For instance, Kinder et al. (2019) observed ceasing of varve preservation in Lake

Szurpiły in a region with minor human-impact and suggested it to be a result of, for instance, ending of arable land use.

In other studied lakes, varve preservation did not terminate despite variations in anthropogenic factors or in climate (Papers I, III). This is expected, as in these lakes, varve preservation is dependent on the lake morphology thus having natural tendency for bottom hypoxia and varve preservation. In these lakes, varve preservation has lasted even from the Medieval warm period through Little Ice Age to the present warming (Haltia-Hovi et al. 2007; Saarni et al. 2015; Saarni 2017).

6 Conclusions

This thesis shows that variations in varve formation, characteristics, and preservation result from responses to variations in climate and human influence. The extent of varve preservation area at the lake floor may vary through time. The onset of an extensive varve preservation period resulting from an increase in hypoxic hypolimnetic water volume seems rather rapid while the return to the baseline extent of varves is more prolonged. This implies that the oxygen deficiency at the lake floor developed rapidly while the recovery to more oxic conditions or to base line conditions took more time. The statistical correlations between the extent of varve preservation (and corresponding hypoxic water volume) and climate parameters suggest that in Lake Lehmilampi variations in varve preservation are dependent on climate rather than anthropogenic factors. Variations in autumn and winter climate seem to have controlled the varve preservation, possibly by influencing the intensity of catchment allochthonous organic matter and nutrient influx, stratification, and autumn overturn periods. This study fortifies that using the spatial presence of varves to study changes in hypolimnetic hypoxia is a suitable approach.

Unlike in Lake Lehmilampi, anthropogenic influence triggered the varve preservation in Lake Vesijärvi starting from the late 1930s. Varve preservation and characteristics changed related to the development of cultural eutrophication and subsequent rehabilitation actions. However, varve preservation did not completely end during the biomanipulation and management fishing, although varve preservation had already weakened prior to the onset of biomanipulation in response to the start of sewage diversion. Finally, the varve formation and preservation terminated in the Enonsaari Deep in the 2010s because of turbulence-induced erosion caused by the aerator.

This thesis reveals a high potential of biogenic lamina thickness for paleoclimate studies. The results suggest that variations in biogenic lamina thicknesses are dependent on growing season and open water season climate. High growing season temperature and open water season precipitation result in thicker biogenic laminae through increased primary production. This is explained by intensified primary production during warm growing season as well as the enhanced supply of allochthonous biogenic matter and nutrients following open water season with high precipitation. This finding is valuable information that enables the use of varve records in reconstructing past growing season and open water season climate in addition to winter climate.

This study highlights the importance of climate and human-induced changes in catchment and lake bottom dynamics for varve formation, preservation, and characteristics and provides understanding on how human actions can change conditions in lake systems. The results of this study are greatly beneficial for climate reconstructions and valuable also when reconstructing cultural eutrophication histories and protecting lacustrine environments.

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List of References

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., Weyheneyer, G.A. & Winder, M. 2009. Lakes as sentinels of climate change. *Limnology and Oceanography,* 54, p. 2283–2297.

Amann, B., Szidat, S., & Grosjean, M. 2015. A millennial-long record of warm season precipitation and flood frequency for the North-western Alps inferred from varved lake sediments: implications for the future. *Quaternary Science Reviews*, 115, p. 89‒100.

Amann, B., Lamoureux, S. F., & Boreux, M. P. 2017. Winter temperature conditions (1670–2010) reconstructed from varved sediments, western Canadian High Arctic. *Quaternary Science Reviews*, 172, p. 1‒14.

Arnaud, F., Poulenard, J., Giguet-Covex, C., Wilhelm, B., Révillon, S., Jenny, J. P., Revel, M., Enters, D., Bajard, M., Fouiant, L., Doyen, E., Simonneau, A., Pignol, C., Chapron, E., Vannière, B. & Sabatier, P. 2016. Erosion under climate and human pressures: An alpine lake sediment perspective. *Quaternary Science Reviews*, 152, p. 1‒18.

Battarbee, R. W., Jones, V. J., Flower, R. J., Cameron, N. G., Bennion, H., Carvalho, L. & Juggins, S. 2001. Diatoms. In: *Tracking Environmental Change Using Lake Sediments* Volume 3. (ed) Smol, J.P., Birks, H. J. B., Last, W. M., Kluwer Academic Publishers: Dordrecht, The Netherlands, p. 155‒202.

Boehrer, B. & Schultze, M. 2008. Stratification of lakes. *Reviews of Geophys*ics, 46(2), p. 1‒27.

Bonk, A., Müller, D., Ramisch, A., Kramkowski, M. A., Noryśkiewicz, A. M., Sekudewicz, I., Gąsiorowski, M., Luberda-Durnaś, K., Słowiński, M., Schwab, M., Tjallingii, R., Brauer, A. & Błaszkiewicz, M. 2021. Varve microfacies and chronology from a new sediment record of Lake Gościąż (Poland). *Quaternary Science Reviews*, 251.

Bush, M. B., Correa-Metrio, A., Van Woesik, R., Shadik, C. R. & McMichael, C. N. 2017. Human disturbance amplifies Amazonian El Niño–Southern Oscillation signal. *Global change biology*, 23(8), p. 3181‒3192.

Cohen, A. S. 2003. *Paleolimnology: the history and evolution of lake systems*. Oxford university press, New York, 500 p.

Corella, J. P., Moreno, A., Morellón, M., Rull, V., Giralt, S., Rico, M. T., Pérez-Sanz, A. & Valero-Garcés, B. L. 2011. Climate and human impact on a meromictic lake during the last 6,000 years (Montcortès Lake, Central Pyrenees, Spain). *Journal of Paleolimnology*, 46(3), p. 351‒367.

Czymzik M., Haltia E., Saarni S., Saarinen T. & Brauer, A. 2018. Differential North Atlantic control of winter hydroclimate in late Holocene varved sediments of Lake Kortejärvi, eastern Finland. *Boreas*, 47:926‒937.

Diaz, R. J. 2001. Overview of hypoxia around the world. *Journal of environmental quality*, 30(2), p. 275‒281.

Dietze, E., Brykała, D., Schreuder, L. T., Jażdżewski, K., Blarquez, O., Brauer, A., Dietze, M., Obremska, M, Ott, F., Pieńczewska, A., Schouten, S., Hopmans, E. C. & Słowiński, M. 2019. Human-induced fire regime shifts during 19th century industrialization: A robust fire regime reconstruction using northern Polish lake sediments. *PloS one*, 14(9).

Dräger, N., Theuerkauf, M., Szeroczyńska, K., Wulf, S., Tjallingii, R., Plessen, B., Kienel, U. & Brauer, A. 2017. Varve microfacies and varve preservation record of climate change and human impact for the last 6000 years at Lake Tiefer See (NE Germany). *The Holocene*, 27(3), p. 450–464.

Dräger, N., Plessen, B., Kienel, U., Słowiński, M., Ramisch, A., Tjallingii, R., Pinkerneil, S. & Brauer, A. 2019. Hypolimnetic oxygen conditions influence varve preservation and δ 13 C of sediment organic matter in Lake Tiefer See, NE Germany. *Journal of Paleolimnology*, 62(2), p. 181–194.

FEI – Finnish Environment Institute 2018. Corine Land Cover. Available online: <https://www.syke.fi/en-US/Open_ information/Spatial_datasets> Accessed on 13 August 2020.

FMI – Finnish Meteorological Institute: Seasons in Finland. Available online: https://en.ilmatieteenlaitos.fi/seasons-in-finland. Accessed on 3 December 2021.

FMI database – Finnish Meteorological Institute database. Available online: https://en.ilmatieteenlaitos.fi/statistics-from-1961-onwards. Accessed on 14 April 2020

Friedrich, J., Janssen, F., Aleynik, D., Bange, H. W., Boltacheva, N., Çagatay, M. N., Dale, A. W., Etiope, G., Erdem, Z., Geraga, M. et al. 2014. Investigating hypoxia in aquatic environments: Diverse approaches to addressing a complex phenomenon. *Biogeosciences*, 11, p. 1215–1259.

Gaglioti, B. V., Mann, D. H., Jones, B. M., Wooller, M. J. & Finney, B. P. 2016. High-resolution records detect human-caused changes to the boreal forest wildfire regime in interior Alaska. *The Holocene*, 26(7), p. 1064–1074.

Grimm, E. C. 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and geosciences*, 13(1) p. 13–35.

Guiry, M. D. & Guiry, G. M. 2018. AlgaeBase. World-Wide Electronic Publication, National University of Ireland, Galway. Available online: <http://www.algaebase.org> Accessed on 11 September 2020.

Hakala, A. 2004. Meromixis as a part of lake evolution; observations and a revised classification of true meromictic lakes in Finland. *Boreal Environmental Research,* 9(1), p. 37–53.

Hakku Database. Geological Survey of Finland 2015. Superficial Deposits. Available online: <https://hakku.gtk.fi/en/locations/search> Accessed on 11 January 2020.

Hanson, P. C., Buffam, I., Rusak, J. A., Stanley, E. H. & Watras, C. 2014. Quantifying lake allochthonous organic carbon budgets using a simple equilibrium model. *Limnology and Oceanography*, 59(1) p. 167–181.

Haltia-Hovi, E., Nowaczyk, N. & Saarinen, T. 2010. Holocene palaeomagnetic secular variation recorded in multiple lake sediment cores from eastern Finland. *Geophysical Journal International*, 180(2), p. 609–622.

Haltia-Hovi, E., Nowaczyk, N. & Saarinen, T. 2011. Environmental influence on relative palaeointensity estimates from Holocene varved lake sediments in Finland. *Physics of the Earth and Planetary Interiors*, 185(1-2), p. 20–28.

Haltia-Hovi, E., Saarinen, T. & Kukkonen, M. 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews*, 26(5–6), p. 678–689.

Hayes, N.M., Deemer, B.R., Corman, J.R., Razavi, N.R. & Strock, K.E. 2017. Key differences between lakes and reservoirs modify climate signals: A case for a new conceptual model. *Limnology and Oceanography Letters,* 2, p. 47–62.

Hernández-Almeida, I., Grosjean, M., Gómez-Navarro, J. J., Larocque-Tobler, I., Bonk, A., Enters, D. Ustrzycka, A., Piotrowska, N., Przybylak, R., Wacnik, A., Witak, M. & Tylmann, W. 2017. Resilience, rapid transitions and regime shifts: Fingerprinting the responses of Lake Żabińskie (NE Poland) to climate variability and human disturbance since AD 1000. *The Holocene* 27(2), p. 258–270.

HERTTA database. Available online: <https://www.syke.fi/en-US/Open_information> Accessed on 27 August 2021.

Hyttinen, O., Salonen, V. P. & Kaakinen, A. 2011. Depositional evidence of water-level changes of the Baltic Ice Lake in southern Finland during the Younger Dryas/Holocene transition. *GFF,* 133(1–2), p. 77–88.

Itkonen, A. & Salonen, V. P. 1994. The response of sedimentation in three varved lacustrine sequences to air temperature, precipitation and human impact. *Journal of Paleolimnology*, 11(3), p. 323–332.

Jankowski, T., Livingstone, D.M., Bührer, H., Forster, R. & Niederhauser, P. 2006. Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world. *Limnology and Oceanography,* 51, p. 815–819.

Jenny, J. P., Arnaud, F., Dorioz, J. M., Giguet Covex, C., Frossard, V., Sabatier, P., Millet, L., Reyss, J. L., Tachikawa, K., Bard, E. et al. 2013. A spatiotemporal investigation of varved sediments highlights the dynamics of hypolimnetic hypoxia in a large hard-water lake over the last 150 years. *Limnology and Oceanography,* 58, p. 1395–1408.

Jenny, J. P., Francus, P., Normandeau, A., Lapointe, F., Perga, M. E., Ojala, A., Schimmelmann, A. & Zolitschka, B. 2016a. Global spread of hypoxia in freshwater ecosystems during the last three centuries is caused by rising local human pressure. *Global Change Biology*, 22, p. 1481–1489.

Jenny, J. P., Normandeau, A., Francus, P., Taranu, Z. E., Gregory Eaves, I., Lapointe, F., Jautzy, J., Ojala, A. E. K., Dorioz, J. M., Schimmelmann, A. & Zolitschka, B. 2016b. Urban point sources of nutrients were the leading cause for the historical spread of hypoxia across European lakes. *PNAS*, 113, p. 12655–12660.

Jilbert, T., Jokinen, S., Saarinen, T., Mattus-Kumpunen, U., Simojoki, A., Saarni, S., Salminen, S., Niemistö, J. & Horppila, J. 2020. Impacts of a deep reactive layer on sedimentary phosphorus dynamics in a boreal lake recovering from eutrophication. *Hydrobiologia*, 847, p. 4401–4423. https://doi.org/10.1007/s10750-020-04289-9

Kairesalo, T. & Vakkilainen, K. 2004. Lake Vesijärvi and the city of Lahti (southern Finland) comprehensive interactions between the lake and the coupled human community. *The International Society of Limnology news*, 41, p. 1–5.

Kalanke, J., Mingram, J., Lauterbach, S., Usubaliev, R., Tjallingii, R., & Brauer, A. 2020. Seasonal deposition processes and chronology of a varved Holocene lake sediment record from Chatyr Kol lake (Kyrgyz Republic). *Geochronology*, 2(1), p. 133–154.

Kamp-Nielsen, L. 1975. A kinetic approach to the aerobic sediment water exchange of phosphorus in Lake Esrom. *Ecological Modelling*, 1, p. 153–160.

Kelly, P. T., Solomon, C. T., Zwart, J. A. & Jones, S. E. 2018. A framework for understanding variation in pelagic gross primary production of lake ecosystems. *Ecosystems*, 21(7), p. 1364–1376.

Keto, J. 1982. The recovery of Lake Vesijärvi after sewage diversion. *Hydrobiologia* 86, p. 195–199.

Keto, J. & Sammalkorpi, I. 1988. fading recovery: A conceptual model for Lake Vesijärvi management and research. *Aqua Fennica,* 18(2), p. 193–204.

Kienel, U., Dulski, P., Ott, F., Lorenz, S. & Brauer, A. 2013. Recently induced anoxia leading to the preservation of seasonal laminae in two NE-German lakes. *Journal of Paleolimnology*, 50(4), p. 535–544.

Kimmel, B. L. & Groeger, A. W. 1984. Factors controlling primary production in lakes and reservoirs: a perspective. *Lake and Reservoir Management*, 1(1), p. 277–281.

Kinder, M., Tylmann, W., Bubak, I., Fiłoc, M., Gąsiorowski, M., Kupryjanowicz, M., Mayr, C., Sauer, L., Voellering, U. & Zolitschka, B. 2019. Holocene history of human impacts inferred from annually laminated sediments in Lake Szurpiły, northeast Poland. *Journal of Paleolimnology*, 61(4), p. 419–435.

Korhonen, J. Suomen Vesistöjen Jääolot. *Finnish Environment*, 751, *Finnish Environment Institute Reports*, Finnish Environment Institute: Helsinki, Finland, 2005; (In Finnish, Summary "Ice Conditions in Lakes and Rivers in Finland" in English); Available online: <https://helda.helsinki.fi/handle/10138/40687> Accessed on 11 June 2021.

Krammer, K. & Lange-Bertalot, H. 1986. Bacillariophyceae, Teil: Naviculaceae. In: Ettle H, Gerloff J, Heynig H, Mollenhauer D (ed) *Süsswasserflora von Mitteleuropa*, Fischer, New York, Band 2/1.

Krammer, K. & Lange-Bertalot, H. 1988. Bacillariophyceae, Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In: Ettle H, Gerloff J, Heynig H, Mollenhauer D, (ed) *Süsswasserflora von Mitteleuropa*, Fischer, Stuttgart New York, Band 2/2.

Krammer, K. & Lange-Bertalot, H. 1991a. Bacillariophyceae, Teil: Centrales, Fragilariaceae, Eunotiaceae. In: Ettle H, Gerloff J, Heynig H, Mollenhauer D, (ed) *Süsswasserflora von Mitteleuropa*, Fisher, Stuttgart, Jena, Band 2/3.

Krammer, K. & Lange-Bertalot, H. 1991b. Bacillariophyceae, Teil: Achnanthaceae. In: Ettle H, Gartner G, Gerloff J, Heynig H, Mollenhauer D (ed) *Süsswasserflora von Mitteleuropa*, Fisher, Stuttgart, Jena, Band 2/4.

Lamoureux, S. F. 1994. Embedding unfrozen lake sediments for thin section preparation. *Journal of Paleolimnology*, 10, p. 141–146.

Lane, S. N., Bakker, M., Costa, A., Girardclos, S., Loizeau, J. L., Molnar, P., Siva, T., Stutenbecker, L. & Schlunegger, F. 2019. Making stratigraphy in the Anthropocene: climate change impacts and economic conditions controlling the supply of sediment to Lake Geneva. *Scientific reports*, 9(1), p. 1–11.

Liukkonen, M., Kairesalo, T. & Haworth, E.Y. 1997. Changes in the diatom community, including the appearance of Actinocyclus normanii f. subsalsa, during the biomanipulation of Lake Vesijärvi, Finland. *European Journal Phycoogyl* 32(4), p. 353–361.

Lotter, A. F., Sturm, M., Teranes, J. L. & Wehrli, B. 1997. Varve formation since 1885 and high-resolution varve analyses in hypertrophic Baldeggersee (Switzerland). *Aquatic Sciences*, 59(4), p. 304–325.

Lotter, A. F. & Lemcke, G. 1999. Methods for preparing and counting biochemical varves. *Boreas*, 28(629), p. 243–252.

Lücke, A. & Brauer, A. 2004. Biogeochemical and micro-facial fingerprints of ecosystem response to rapid Late Glacial climatic changes in varved sediments of Meerfelder Maar (Germany). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 211(1-2), p. 139–155.

Maankamara Digital map database. Available online: <http://gtkdata.gtk.fi/maankamara/> Accessed on 17 June 2020.

Martin-Puertas, C., Tjallingii, R., Bloemsma, M. & Brauer, A. 2017. Varved sediment responses to early Holocene climate and environmental changes in Lake Meerfelder Maar (Germany) obtained from multivariate analyses of micro X-ray fluorescence core scanning data. *Journal of Quaternary Science*, 32(3), p. 427–436.

Miller, D. R., Castañeda, I. S., Bradley, R. S. & MacDonald, D. 2017. Local and regional wildfire activity in central Maine (USA) during the past 900 years. *Journal of Paleolimnology*, 58(4), p. 455–466.

Meriläinen, J. J., Kustula, V., Witick, A., Haltia-Hovi, E. & Saarinen, T. 2010. Pollution history from 256 BC to AD 2005 inferred from the accumulation of elements in a varve record of Lake Korttajärvi in Finland. *Journal of Paleolimnology*, 44(2), p. 531-545.

Meyers, P. A., & Lallier-Vergès, E. 1999. Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. *Journal of Paleolimnology*, 21(3), p. 345–372.

Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes 1. *Journal of Ecology*, 29, p. 280–329.

Mortimer, C.H. 1942. The exchange of dissolved substances between mud and water in lakes 2. *Journal of Ecology*, 30, p. 147–201.

Müller, B., Bryant, L. D., Matzinger, A. & Wüest, A. 2012. Hypolimnetic oxygen depletion in eutrophic lakes. *Environmetal Science & Technology,* 46, p. 9964–9971.

NORDKLIM Dataset (NKDS) v2 2015. Available online: <http://blog.fmi.fi/nordmet/node/214> Accessed on 1 January 2021.

NLS database – National Land Survey of Finland – Old printed maps. Available online: <http://vanhatpainetutkartat.maanmittauslaitos.fi/?lang=en> Accessed on 28 June 2021.

Ohlendorf, C., Niessen, F. & Weissert, H., 1997. Glacial varve thickness and 127 years of instrumental climate data: a comparison. *Climatic Change,* 36, p. 391–411. doi:10.1023/A:1005376913455

Ojala, A. E., Saarinen, T. & Salonen, V-P. 2000. Preconditions for the formation of annually laminated lake sediments in southern and central Finland. *Boreal Environmental Research*, 5(3), p. 243–255.

Ojala, A. E. K. & Alenius, T. 2005. 10000 years of interannual sedimentation recorded in the Lake Nautajärvi (Finland) clastic–organic varves. *Palaeogeography Palaeoclimatology Palaeoecology*, 219, p. 285–302.

Ojala, A. E. K., Francus, P., Zolitschka, B., Besonen, M. & Lamoureux, S. F., 2012. Characteristics of sedimentary varve chronologies – A review. *Quaternary Science Reviews*, 43, p. 45–60. doi:10.1016/j.quascirev.2012.04.006

Ólafsdóttir, S., Reilly, B. T., Bakke, J., Stoner, J. S., Gjerde, M., & van der Bilt, W. G. M. 2019. Holocene paleomagnetic secular variation (PSV) near 80° N, Northwest Spitsbergen, Svalbard: Implications for evaluating High Arctic sediment chronologies. *Quaternary Science Reviews*, 210, p. 90–102.

Paikkatietoikkuna – old aerial photos. Available online: <https://kartta.paikkatietoikkuna.fi/?lang=en> Accessed on 28 June 2021.

Paituli Spatial Data Download Service. National Land Survey of Finland. Available online: <www.csc.fi/paituli> Accessed on 28 June 2021.

Poraj-Górska, A. I., Żarczyński, M. J., Ahrens, A., Enters, D., Weisbrodt, D. & Tylmann, W. 2017. Impact of historical land use changes on lacustrine sedimentation recorded in varved sediments of Lake Jaczno, northeastern Poland. *Catena*, 153, p. 182–193.

Porter, S. P. 2008. Algal Attributes: An Autecological Classification of Algal Taxa Collected by the National Water-Quality Assessment Program. *US Geological Survey Data Series,* p. 329.

R Development Core Team 2016. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing, Vienna, Austria.

Ramsey, C. B., Staff, R. A., Bryant, C. L., Brock, F., Kitagawa, H., Van Der Plicht, J. et al. 2012. A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr BP. *Science*, 338(6105), p. 370–374.

Renberg, I. & Hansson, H. 2008. The HTH sediment corer. *Journal of Paleolimnology* 40, p. 655–65.

Rowell, H. C., Bopp, R. F., Peng, F., Velinsky, D. J. & Bloomfield, J. A. 2015. Annually laminated sediments from Onondaga Lake, New York (USA) provide a basis for high-resolution studies of lake degradation and recovery. *Journal of paleolimnology*, 53(1), p. 107–121.

Saarinen, T. & Wenho, H. 2005. Minijääsormi sekä muita uusia ja vanhoja ideoita järvisedimentin talvikairaukseen. In: Proceedings of the Congress Abstract Book, Geologian Tutkijapäivät, Turku, p. 72–73.

Saarni, S., Saarinen, T. & Lensu, A. 2015. Organic lacustrine sediment varves as indicators of past precipitation changes: a 3,000-year climate record from Central Finland. *Journal of Paleolimnology*, 53, p. 401–413. DOI 10.1007/s10933-015-9832-8

Saarni, S., Muschitiello, F., Weege, S., Brauer, A. & Saarinen, T. 2016. A late Holocene record of solar-forced atmospheric blocking variability over Northern Europe inferred from varved lake sediments of Lake Kuninkaisenlampi. *Quaternary Science Reviews*, 154, p. 100–110.

Saarni, S. 2017. The Sensitivity of Annually Laminated Lake Sediments in Central and Eastern 670 Finland to the Late Holocene Climate. *Annales Universitatis Turkuensis* AII: 331

Saarni, S., Lensu, A., Tammelin, M., Haltia, E. & Saarinen, T. 2017. Winter climate signal in boreal clastic-biogenic varves: a comprehensive analysis of three varved records from 1890 to 1990 AD with meteorological and hydrological data from Eastern Finland. *GFF*, 139(4), p. 314–326.

Saarnisto, M. 1986. Annually laminated lake sediments. In: Berglund, B.E. (ed), *Handbook of Holocene palaeoecology and palaeohydrology*, Chichester, John Wiley, pp. 343–370.

Salmi, P., Malin, I. & Salonen, K. 2014. Pumping of epilimnetic water into hypolimnion improves oxygen but not necessarily nutrient conditions in a lake recovering from eutrophication. *Inland waters,* 4(4), p. 425–434.
Salonen, K., Sarvala, J., Horppila, J., Keto, J., Malin, I., Malinen, T., Niemistö, J. & Ruuhijärvi, J. 2020. Development of Lake Vesijärvi through four decades of remediation efforts. *Hydrobiologia*, 847(21), p. 4601-4619.
Sanchini, A., Szidat, S., Tylmann, W., Vogel, H., Wacnik, A. & Grosjean, M. 2020. A Holocene high-resolution record of aquatic productivity, seasonal anoxia and meromixis from varved sediments of Lake Łazduny, North-Eastern Poland: insight from a novel multi-proxy approach. *Journal of Quaternary Science*, 35(8), p. 1070–1080.
Sinyukovich, V. N. & Chernyshov, M. S. 2019. Water regime of lake Baikal under conditions of climate change and anthropogenic influence. *Quaternary International*, 524, p. 93–101.
Smol, J. P. 2009. *Pollution of lakes and rivers: a paleoenvironmental perspective*. Blackwellspublishing, Malden
Spaulding, S. A., Lubinski, D. J. & Potapova, M. Diatoms of the United States. 2008. Available online: <http://westerndiatoms.colorado.edu > Accessed on 7 February 2019.
Spears, B.M., Carvalho, L., Perkins, R., Kirika, A. & Paterson, D.M. 2007. Sediment phosphorus cycling in a large shallow lake: spatio-temporal variation in phosphorus pools and release. *Hydrobiologia.* 584, p. 37–48 https://doi.org/10.1007/s10750-007-0610-0
Staudinger, S. 2019. Suomi, 57 000 – 168 000 järven maa. National Land Survey of Finland. Available online: <https://www.maanmittauslaitos.fi/ajankohtaista/suomi-57-000-168-000-jarven-maa> Accessed on 25 August 2021.
Straile, D., Johnk, K. & Rossknecht, H. 2003. Complex effects of winter warming on the physicochemical characteristics of a deep lake. *Limnology and Oceanography* 48, p. 1432–1438.
Striberger, J., Björck, S., Ingólfsson, ó., Kjaer, K.H., Snowball, I. & Uvo, C. B. 2011. Climate variability and glacial processes in eastern Iceland during the past 700 years based on varved lake sediments: Climate variability and glacial processes in eastern Iceland. *Borea*s, 40, p. 28–45. doi:10.1111/j.1502-3885.2010.00153.x
Tammelin, M., Kauppila, T. & Viitasalo, M. 2017. Factors controlling recent diatom assemblages across a steep local nutrient gradient in central-eastern Finland. *Hydrobiologia,* 799, 3 p. 09–325.
Tammelin, M. & Kauppila, T. 2018. Quaternary landforms and basin morphology control the natural eutrophy of boreal lakes and their sensitivity to anthropogenic forcing. *Frontiers of Ecology and Evolution* 6(65).
Ter Braak, C. J. F. & Šmilauer, P. 200. 2CANOCO Reference Manual and Cano Draw for Windows User's Guide: Software for Canonical Community Ordination; Version 4.5; Microcomputer Power: Ithaca, NY, USA.
Tiljander, M., Ojala, A., Saarinen, T. & Snowball, I. 2002. Documentation of the physical properties of annually laminated (varved) sediments at a sub-annual to decadal resolution for environmental interpretation. *Quaternary International,* 88, p. 5–12.
Tiljander, M., Saarnisto, M., Ojala, A.E., Saarinen, T. 2003. A 3000-year palaeoenvironmental record from annually laminated sediment of Lake Korttajarvi, central Finland. *Boreas*, 32, p. 566–577.
Tiljander, M. 2005. Holocene sedimentary history of annual laminations of Lake Korttajärvi, central Finland. *Publications of the Department of Geology D5*. University of Helsinki.
Topographic Database. National Land Survey of Finland 2017. Available online: ≤https://tiedostopalvelu.maanmittauslaitos.fi/tp/kartta?lang=en> Accessed on 27 February 2021.
Tylmann, W., Zolitschka, B., Enters, D. & Ohlendorf, C. 2013. Laminated lake sediments in northeast Poland: distribution, preconditions for formation and potential for paleoenvironmental investigation. *Journal of Paleolimnology*, 50, p. 487–503.
Vos, H., Sanchez, A., Zolitschka, B., Brauer, A. & Negendank, J. F. 1997. Solar activity variations recorded in varved sediments from the crater lake of Holzmaar–A maar lake in the Westeifel volcanic field, Germany. *Surveys in Geophysics*, 18(2), p. 163–182.

Zander, P. D., Żarczyński, M., Tylmann, W., Rainford, S. K. & Grosjean, M. 2021. Seasonal climate signals preserved in biochemical varves: insights from novel high-resolution sediment scanning techniques. *Climate of the Past Discussions*, p. 1–24.

Zolitschka, B., Francus, P., Ojala, A. E. & Schimmelmann, A. 2015. Varves in lake sediments—A review. *Quaternary Science Reviews,* 117, p. 1–41.

Zolitschka, B., Behre, K. E., & Schneider, J. 2003. Human and climatic impact on the environment as derived from colluvial, fluvial and lacustrine archives—examples from the Bronze Age to the Migration period, Germany. *Quaternary Science Reviews*, 22(1), p. 81–100.

Zolitschka, B. 1998. A 14,000 year sediment yield record from western Germany based on annually laminated lake sediments. *Geomorphology*, 22(1), p. 1–17.

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