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ORIGINAL PAPER

Sensitivity of varve biogenic component to climate in eastern and central Finland

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Abstract Biogenic varves as well as the biogenic component of clastic–biogenic varves have great potential as climate and environmental proxies but the response of biogenic lamina thickness to variations in growing-season climate is not well known. The connection of biogenic lamina thickness with growing-season or open-water season climate has been the focus of a limited number of studies. We examined biogenic laminae deposited during the past 100 years in five Finnish lakes representing different catchment types. We compared variations in biogenic lamina thicknesses with growing-season temperature records and open-water-season precipitation records. Statistical analyses for the whole study period reveal that the studied lakes generally respond positively to variations in growing-season temperature and open-water season precipitation. This suggests that warm summers intensify primary production while precipitation enhances transportation of allochthonous biogenic material and nutrients into the lake. Both mechanisms lead to enhanced biogenic lamina thickness. Two lakes reveal a more complex relationship to climate. Biogenic lamina thicknesses record a distinguishable climate signal despite human activities in the catchments, such as peatland drainage and forest cutting. We conclude that variations in biogenic lamina thickness of such boreal (clastic)–biogenic varves show potential for growing-season climate reconstructions. However, the response of each lake to climate parameters should be tested and understood separately.

Keywords Climate forcing · Summer climate · Clastic–biogenic varves · Growing season · Human influence

Introduction

Future climate scenarios predict global rise of temperatures and spatial changes in rainfall (IPCC 2021). Larger changes in climate are estimated to take place at high latitudes with major influence on winter season. However, shifts in summer conditions are expected, especially in form of summer-heat-wave frequency and/or intensity, which are likely to increase in Northern Europe (Della-Marta et al. 2007; Perkins et al. 2012; Perkins-Kirkpatrick et al. 2017; IPCC 2021). Furthermore, the periods of droughts are predicted to influence on future freshwater cycles and groundwater availability (Taylor et al. 2013; Mosley 2015). The regional response to climate change is expected to vary between seasons and

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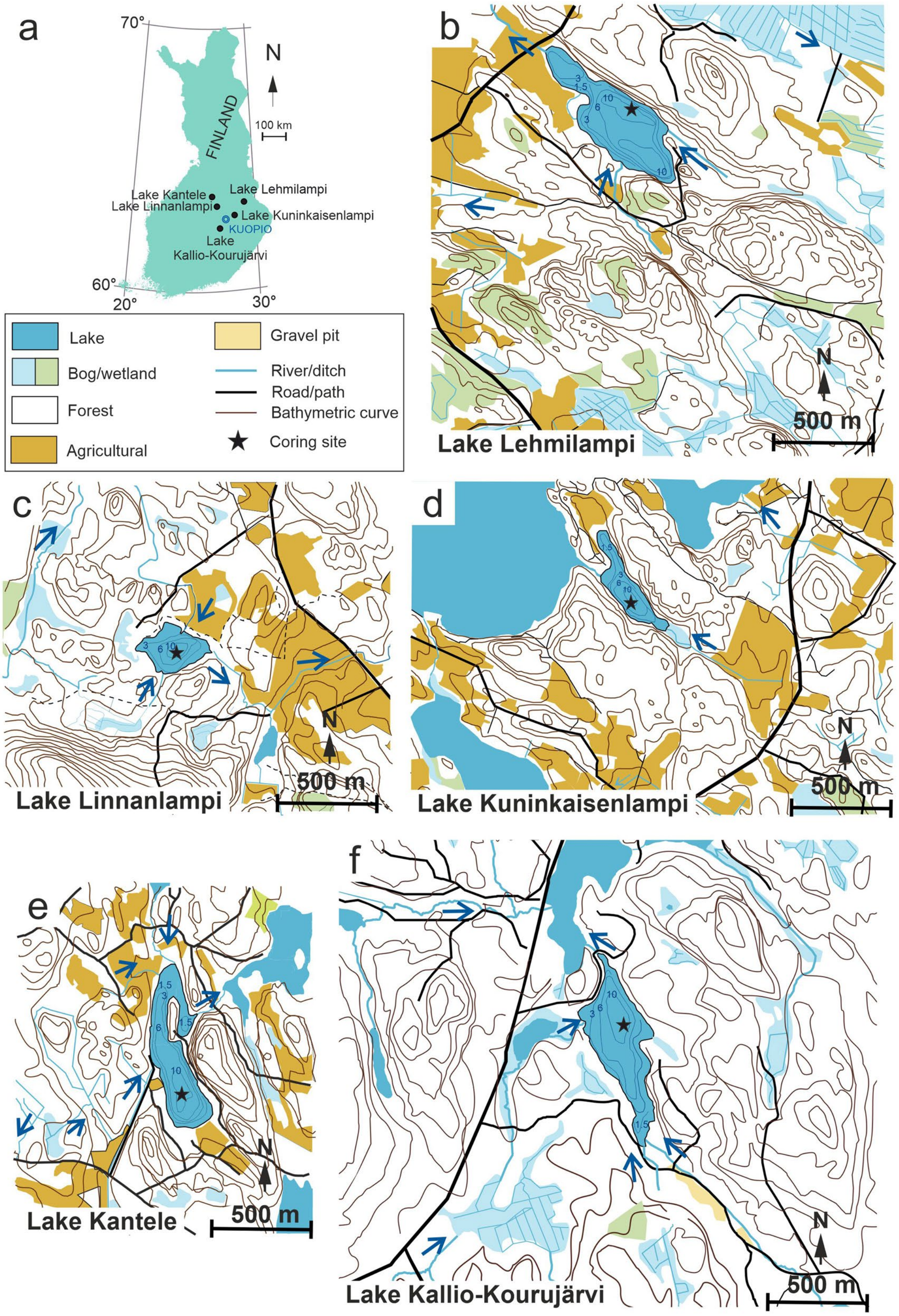
a
70°
N
100 km
FINLAND
Lake Kantele
Lake Lehmilampi
Lake Linnanlampi
Lake Kuninkaisenlampi
KUOPIO
Lake
Kallio-Kourujärvi
60°
20°
30°
Lake
Gravel pit
Bog/wetland
River/ditch
Forest
Road/path
Bathymetric curve
Agricultural
Coring site
b
3
1.5
6
10
3
10
N
500 m
Lake Lehmilampi
c
3
6
10
N
500 m
Lake Linnanlampi
d
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3
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10
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Lake Kuninkaisenlampi
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6
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500 m
Lake Kantele
f
10
3
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500 m
Lake Kallio-Kourujärvi

◂**Fig. 1** Lake locations, coring sites, and the nearby catchments. **a** Locations of the studied lakes and the Kuopio meteorological station in Finland. **b**–**f** Catchment characteristics in the vicinity of the studied lakes. The coring sites are marked with stars

latitudes leading to a demand of season-specific climate-proxy data from all climatic zones. In order to improve future predictions and societal mitigation to the regional changes, such season-specific long-term paleoclimate records covering the entire Holocene are critical (Kwiecien et al. 2022).

Annually laminated, i.e., varved sediments are one of the proxies to assess seasonality changes due to their excellent temporal resolution as well as their accurate and precise time control and potentially long temporal extent up to tens of thousands of years (e.g., Larocque-Tobler et al. 2015; Zolitschka et al. 2015). These sediments are formed through annual cycles influencing water bodies and their catchments controlling the availability and characteristics of accumulating material (O'Sullivan 1983; Zolitschka et al. 2015; Kwiecien et al. 2022). Varves typically consist of two or more laminae with distinct characteristics representing different seasons (Cuven et al. 2011; Czymzik et al. 2013; Saarni et al. 2016a; Zander et al. 2021). Hence, they can be analyzed in sub-annual scale in order to reconstruct seasonal climate for thousands of years back in time (Dean et al. 1999; Ojala et al. 2000; Lapointe et al. 2019; Żarczyński et al. 2019).

Large seasonal variations in the boreal climate zone provide favorable conditions for varve formation, and there is a large number of varve records that shed light on past climate variation (Zolitschka et al. 2015). Clastic lamina (CL) thickness is reported to reflect variations in spring temperature and winter precipitation (Saarni et al. 2017) and has been widely used to reconstruct past changes in winter climate (Haltia et al. 2007; Ojala and Alenius 2005). However, only few studies discuss the response of varve biogenic component or its thickness to climate (Saarni et al. 2015; Sanchini et al. 2020; Zander et al. 2021). While seasonal variability can influence the biogenic lamina (BL) thicknesses (Saarni et al. 2015) the BL has undiscovered potential to reflect growing season or open-water-season climate.

Lakes may respond very differently to variations in climate (Adrian et al. 2009; Winslow et al. 2015; Saarni et al. 2017) and hence the processes behind varve formation in each varve record should be understood in detail prior to using a varve record in climate studies. This is because varve characteristics and thickness are affected not only by autochthonous production and degradation but also by the availability of allochthonous material which, in turn, is controlled by catchment topography, morphology, and soil types (Ojala et al. 2012; Zolitschka et al. 2015) as well as anthropogenic activities (Kienel et al. 2013; Lane et al. 2019; Salminen et al. 2021). For instance, Saarni et al. (2017) stated that the mechanisms by which climate forcing affects the sediment record is ultimately controlled by catchment characteristics. It has also been observed that varve characteristics are unidentical even in adjacent lakes because of differences in catchment types and land use between the lakes (Gälman et al. 2006). These previous observations highlight the need to examine and compare multiple lacustrine varve records to investigate the potential of BL thickness as a proxy for growing season and open-water-season climate.

The changes in growing-season temperature and precipitation lead to variations in autochthonous productivity and transport of allochthonous material into lakes which further impacts the availability of nutrients, light-penetration depth and oxygen consumption at the lake floor. Comprehending the impact of summer climate is a prerequisite for evaluating the future change in lake systems but also a key to examine BL thickness as a proxy for growing-season conditions.

In this study, we investigated five boreal varve records from lakes with varying catchments to understand the BL-thickness response to varying climate conditions. We used growing season and open-water-season data and BL thicknesses for correlation analysis to further investigate the sensitivity of BL thickness to growing-season temperature and precipitation in the studied lakes and to explore the potential of BL thickness as growing-season climate proxy.

Study site

The study area (6000 km^2) consists of five lakes in eastern and central Finland (lakes Kallio-Kourujärvi, Kantele, Kuninkaisenlampi, Lehmilampi, and Linnanlampi) (Fig. 1). All the lakes are of glacial origin, remote, and lie in the boreal climate zone (Table 1; Ahti et al. 1968). The lakes are small, their sizes range from 0.05 to 0.17 km^2 and the catchments from

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

	Lake Kallio-Kourujärvi	Lake Kantele	Lake Kuninkaisenlampi	Lake Lehmilampi	Lake Linnanlampi
Location coordinates	62° 34′ N, 27° 01′ E	63° 29′ N, 26° 39′ E	62° 58′ N, 28° 14′ E	63° 37′ N, 29° 06′ E	63° 19′ N, 27° 10′ E
Surface area (km^2)	0.13	0.1	0.05	0.17	0.05
Catchment area (km^2)	10.0	1.0	1.1	1.0	9.0
Catchment area / surface area ratio	76.9	10	22	5.9	180
Maximum water depth (m)	11.0	12.0	10.1	11.6	11.0
Main surface deposits and outcrops in the nearby catchment	Many outcrops, mixed soil type, sandy till	Mixed soil type	Mixed soil type, fine-grained soil type	Sandy till, silt, and clay	Fine-grained till
Bedrock in the nearby catchment	Porphyritic quartz monzonite, porphyritic granite, granodiorite	Pyroxene granite, enderbite, diorite	Tonalite, tonalitic migmatite, biotite paragneiss	Migmatitic tonalite, biotite paragneiss	Gabbro, tonalite, biotite paragneiss
Trophic status and additional information	Oligotrophic	Eutrophic	Eutrophic	Eutrophic, headwater lake	Eutrophic
Historical events in the catchment	Peatland ditching 1973–1988, forest cutting 1988–1994, road constructions 1944–1988, start of gravel extraction 1939–1973, agricultural field foresting 1973–1988	Forest cutting 1953–1994, road constructions 1953–1991	Forest cutting 1939–1994, Road constructions 1973–1990	Peatland ditching 1977–1992, forest cutting (minimal) 1941–1976, road construction 1941–1976, 1984–1992	Peatland ditching 1973–1991, forest cutting 1973–1991, agricultural field foresting 1973–1991

1.0 to 10.0 km^2 (Table 1). All the lakes, except for Lake Linnanlampi, are elongated in northwest-southeast or north–south orientation (Fig. 1). Maximum water depths range from 10.1 to 12.0 m (Table 1). In all five lakes, the varve records span thousands of years and are characterized by clastic–biogenic varve structure, except for Lake Kallio-Kourujärvi, in which varves are biogenic (Haltia-Hovi et al. 2007; Saarni et al. 2015; Saarni 2017; Salminen et al. 2019). The catchments of lakes Kantele, Kuninkaisenlampi, and Linnanlampi contain nutrient-rich soil types, such as fine-grained till (Lintinen et al. 1995), that favors natural eutrophication (Tammelin et al. 2017; Tammelin and Kauppila 2018) and consequent oxygen deficiency at the lake floor.

The climate in the study area is characterized by mild summers and snowy winters. Mean annual, spring, summer, autumn, and winter temperatures are 3.2, 2.2, 15.2, 3.7, and − 8.5 °C, respectively (Kuopio meteorological station, FMI database). Mean annual precipitation is 626 mm whereas mean spring, mean summer, mean autumn, and mean winter precipitations are 111, 222, 161, and 132 mm, respectively (Kuopio meteorological station, FMI database). During winter, precipitation accumulates mainly as snow. Spring overturns typically occur in May and autumn overturns in September–October (HERTTA database). Ice-cover duration ranges from 90 to 210 days (Korhonen 2005). Highest wind velocities occur in autumn and the lowest during winter. In autumn, wind direction is mostly southeasterly and during the rest of the year southwesterly.

Materials and methods

Sediment coring

The sediment coring was performed on the lake ice during the winters 2008–2009 and the spring 2014. A Livingston-type piston corer and a HTH sediment corer (Renberg and Hansson 2008) were used for coring the sediment at the deepest point of each lake (Fig. 1). The freeze cores were taken from the HTH samples using the ice-finger technique (Saarinen and Wenho 2005) to ensure no topmost varves were lost. At least one sediment core and one freeze core (length: ~ 30 cm) were collected from each lake.

Laboratory work

The piston corer and freeze-corer samples were split lengthwise. The piston-corer samples were sub-sampled by extracting 11-cm-long sediment blocks with a 1.5-cm overlap. The freeze-corer samples were sub-sampled by cutting the halved samples into two with 2-cm overlap. To preserve the detailed varve structure, the sub-samples were embedded with Spurr low viscosity epoxy resin following the water–acetone-epoxy exchange method (Lamoureux 1994; Tiljander et al. 2002). The embedded samples were cut using a rock saw and thin sections were prepared following the technique of Lotter and Lemcke (1999). The sample grinding and polishing was carried out manually or automatically with an ASTERA CUT8 diamond saw and ASTERA GRN16 grinder. Either way, the final polishing was made manually.

Varve dating and measurements

Varves were characterized and counted to the top of each core from thin sections using a Leitz Laborlux petrographic microscope coupled with a Euromex HD-Ultra camera and alternatively a Nikon SMZ800 stereomicroscope coupled with Canon EOS Utility software. However, varves from 1999 towards present were excluded due to uncompacted topmost varves. The exclusion was determined based on magnetic susceptibility. Varve counting was carried out three times and the deviation in these counts was used to evaluate the error margins for each varve chronology (Lotter and Lemcke 1999). BL thicknesses were measured with the aforementioned stereomicroscopes to study the correspondence of variations in sedimentation and climate.

To verify the varve chronologies of Lakes Kantele and Linnanlampi cores, ^{137}Cs activity measurements were carried out at the Geological Survey of Finland with a BrightSpec gamma spectrometer (3600 s counting time). In the activity measurements, a continuous series of fresh sediment sub-samples from Lake Kantele (integrating no more than 7 varves), and from Lake Linnanlampi (integrating no more than 5 varves), were analyzed.

Climate data and statistical analyses

To study possible climatic factors triggering changes in sedimentation, meteorological data of Kuopio meteorological station (NORDKLIM) were acquired. The data of Kuopio meteorological station were considered suitable because of the distance of the station to the studied lakes and the continuity of the measurement data. The studied lakes are located 34 km (Lake Kuninkaisenlampi), 48 km (Lake Kallio-Kourujärvi), 54 km (Lake Linnanlampi), 85 km (Lake Kantele), and 107 km (Lake Lehmilampi) from Kuopio meteorological station. Based on the available long meteorological data series, the difference between meteorological data from two meteorological stations in the study area (Kuopio and Kajaani meteorological stations, 171 km apart) is less than 10.1% (NORDKLIM). The monthly temperature (T) and precipitation (R) data that were used cover the time period of 1891–1998 and 1890–1998, respectively. Mean annual growing season (mean daily temperature above 5.0 °C, FMI) temperature (April–September) and mean annual open-water season (ice-free period) precipitation (April–November) were calculated from the acquired meteorological data. The open-water-season precipitation was investigated instead of growing season precipitation because organic matter transport following the autumn rains, is hypothesized to have significant influence on the BL thickness.

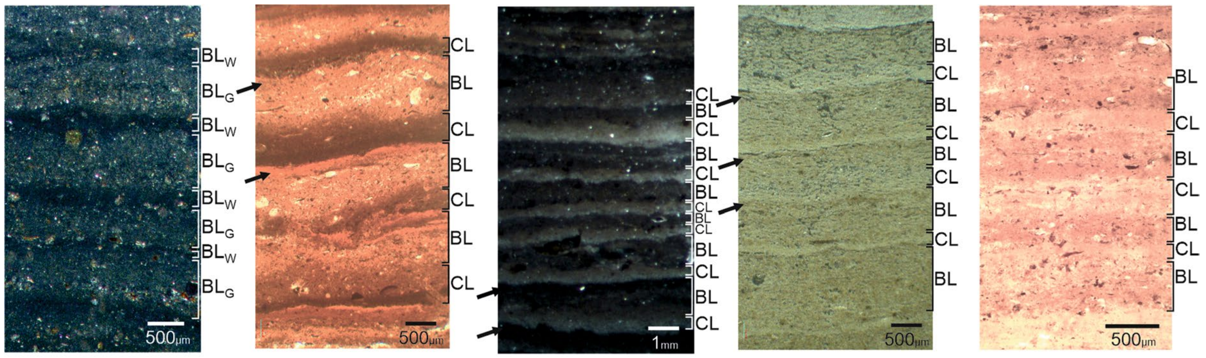
Correlations between meteorological data and BL thickness for the whole study period were calculated for each lake. Because we observed poor correlations for the whole study period in lakes Kallio-Kourujärvi and Kantele, we investigated correlations for shorter time intervals for these two lakes. We chose two periods for each variable based on their statistical significance, length, and correlation strength. The first period starts from the beginning of the study period, and ends when the second period starts. To calculate the correlations, we used the software R3.4.3 (R Development Core Team 2016) to identify possible statistically significant covariates. To minimize the effect of possible inaccuracies in varve counting and to regard decadal trends in climate data, an 11-year running mean was applied to BL and climate data (Itkonen and Salonen 1994). Spearman's Rank Correlation analysis was used to calculate the correlations because in each case one or the other studied variable was not normally distributed.

Results

Varve types and biogenic lamina thicknesses

During the studied period (1890–2000 AD) the varve chronology is continuous with the varves distinguishable in all five studied lakes. In lakes Kantele, Kuninkaisenlampi, Lehmilampi, and Linnanlampi, the varves are composed of a CL and a BL, i.e., the varve type is clastic–biogenic (Fig. 2). The varve year of the clastic–biogenic varve type begins abruptly with a clastic material dominated lamina formed as a consequence of spring floods resulting from snow and ice melt in spring. CL changes gradually to organic matter-rich BL deposited mostly during the growing season. BL terminates in a thin, fine-grained amorphous organic matter sub-lamina that accumulates under ice cover (Fig. 2; Ojala et al. 2013). While the main component in CL is a mixture of mineral grains, in the BL, amorphous organic matter, organic fragments, and micro-organism remains dominate. In Lake Linnanlampi, the change from CL to BL is more abrupt and the color of BL lighter than in other studied lakes with clastic–biogenic varves. In all these lakes, the color of BL is darker than that of CL. The color contrast between CL and BL is most pronounced in Lake Kuninkaisenlampi. In the BL of lakes Lehmilampi and Linnanlampi, dark and thin sub-laminae are present.

In Lake Kallio-Kourujärvi, the varve type is biogenic where both of the two separable sub-laminae are composed of biogenic matter (Fig. 2). However, occasional CL is found at the topmost 9 cm of the Lake Kallio-Kourujärvi sediment (Saarni et al. 2015). The two biogenic sub-laminae in Lake Kallio-Kourujärvi differ notably from each other enabling varve counts (Saarni et al. 2015). The BL sub-lamina BL_G that begins the varve year, is composed of degraded organic matter that is deposited during growing season. The varve year ends with the BL sub-lamina BL_W that consists of fine-grained amorphous organic matter deposited during ice cover. BL_W is equivalent to the sub-lamina in which the BL of clastic–biogenic varve type terminates in. The BL_G and BL_W of Lake Kallio-Kourujärvi together form the BL. BL_G thickness was used for correlation analysis. The total varve thicknesses in the studied lakes ranges from 0.25 to 3.80 mm and BL thickness from 0.10 to 3.25 mm (Table 2). The BL thickness fluctuates in all lakes



Lake Kallio-Kourujärvi

Lake Kantele

Lake Kuninkaisenlampi

Lake Lehmilampi

Lake Linnanlampi

Fig. 2 Microscope images showing the varve structures of the studied lakes. BL and CL are marked. In addition, arrows point out examples of the fine-grained biogenic sub-laminae of topmost BL in clastic–biogenic varve type. Microscope images of lakes Kantele, Lehmilampi, and Linnanlampi are taken with a petrographic microscope from thin sections. Microscope image of Lake Kuninkaisenlampi is a stereomicroscope image of 1.8-mm-thick epoxy-embedded sediment section and the image of Lake Kallio-Kourujärvi is a stereomicroscope image of the thin section using dark field illumination. In Lake Kallio-Kourujärvi, BL_W means the sub-lamina that consists of material deposited during winter-ice-cover and ends the varve year (equivalent to the topmost sub-lamina of BL in clastic–biogenic varve type pointed out with arrows), and BL_G the sub-lamina that is composed of degraded organic matter deposited during growing season

Table 2 Variations in total varve thickness (TOT) and BL thickness. Means of TOT and BL are also provided. For Lake Kallio-Kourujärvi, BL refers to BL_G

	Lake Kallio-Kourujärvi	Lake Kantele	Lake Kuninkaisenlampi	Lake Lehmilampi	Lake Linnanlampi
TOT (mm)	0.30–1.80	0.33–3.71	0.40–3.80	0.28–2.28	0.25–3.09
TOT_{mean} (mm)	0.79	1.39	1.21	1.10	1.34
BL (mm)	0.10–1.50	0.20–3.25	0.13–2.41	0.40–2.40	0.16–2.15
BL_{mean} (mm)	0.57	1.14	0.82	1.02	0.74

during the studied period and shows an increasing trend towards present day, except in the case of Lake Kallio-Kourujärvi where BL has decreased since the 1980s (Figs. 3, 4a). The BL thickness peaks at different times among the dated cores.

Varve chronology and ^{137}Cs activity

Error estimates for sediment chronologies of lakes Kantele and Linnanlampi are −0.7 to +0.7% and −1.0 to +1.0%, respectively (Saarni et al. 2017). Lake Lehmilampi error estimate is −0.5 to +0.5% (Salminen et al. 2019) whereas for Lakes Kallio-Kourujärvi and Kuninkaisenlampi they are −2.5 to +2.3% and −1.0 to +0.8%, respectively (Saarni et al. 2015, 2016b). Because the boundary between BL and CL is progressive and no imaging techniques were applied in BL thickness measurements, the accuracy of BL thickness measurements remains undetermined.

^{137}Cs activity peaks representing the 1986 Chernobyl nuclear accident were found in Lake Kantele and Lake Linnanlampi sediments at depths of 2.0–3.0 and 2.5–5.5 cm (Fig. 4b), respectively, and agree with varve counting. A minor peak corresponding to the year 1963 fallout from atmospheric nuclear weapons testing was found in Lake Kantele sediment at depth of 5.0–7.0 cm (Fig. 4b). The magnitudes of the year 1986 ^{137}Cs peak values of Lake Kantele (162 Bq kg^{-1}) were greater than the 1963 peak, which is typical for this part of the world (Appleby 2002; Lusa et al. 2009; Haltia et al. 2021). The verification of varve counting of other studied lakes has been provided earlier by Saarni et al. (2015: Lake

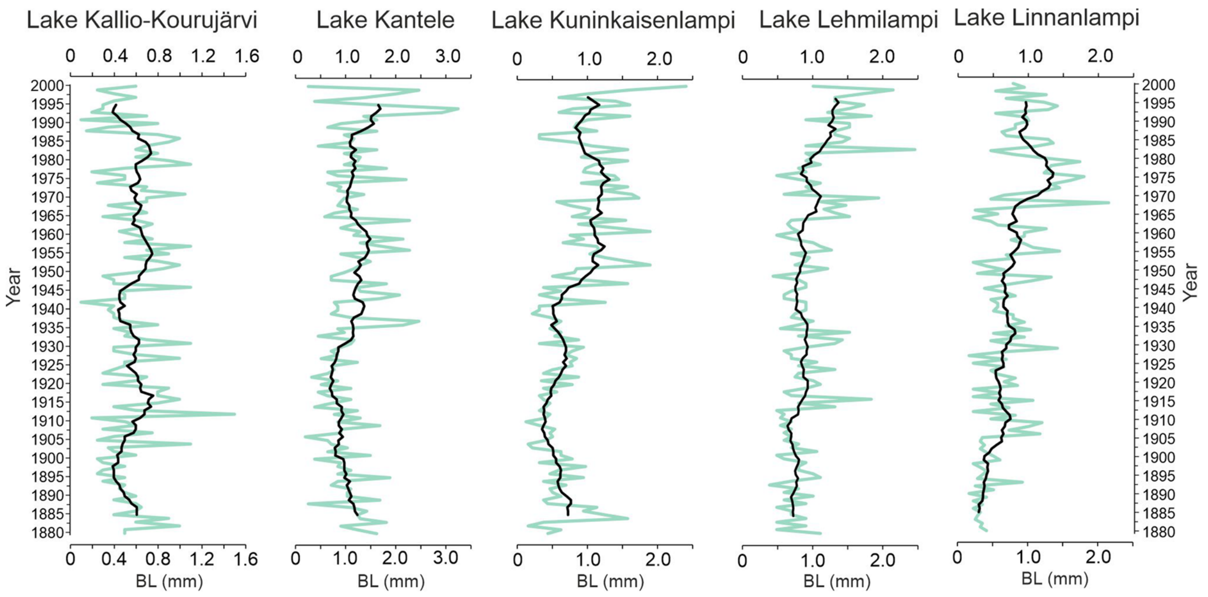


Fig. 3 Variations in BL thickness in the studied lakes. Shaded green line shows variations in BL annual thickness and black line in 11-year mean in BL thickness. For Lake Kallio-Kourujärvi, BL refers to BL_G

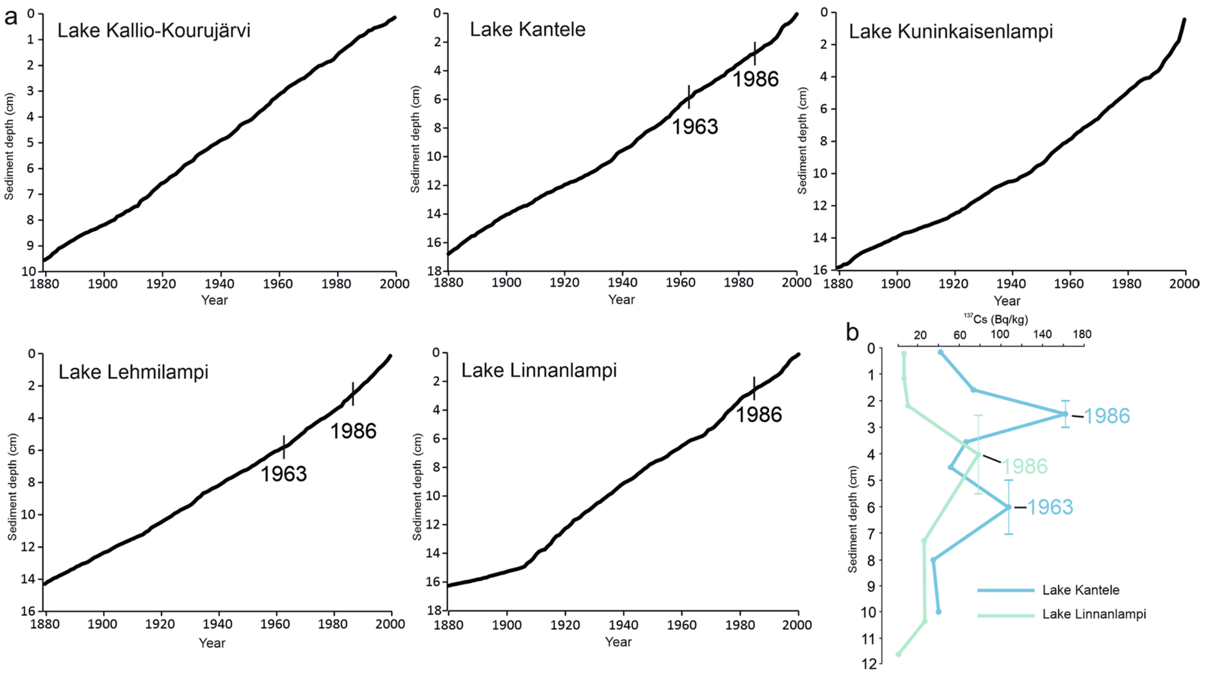


Fig. 4 **a** Age versus sediment-depth curves for the studied lakes. Varve counting-based time markers of lakes Kantele, Lehmilampi, and Linnanlampi are shown to highlight the agreement of ^{137}Cs activity peaks of years 1963 and 1986 and varve counting **b** ^{137}Cs activity of Lakes Kantele and Linnanlampi. Note that the vertical line segments show the sediment depths where the sub-samples for ^{137}Cs activity measurements were taken. Line segments are provided only for the sediment depths with year 1963 and 1986 peaks

Kallio-Kourujärvi; 2016b: Lake Kuninkaisenlampi), and Salminen et al. (2019: Lake Lehmilampi).

Variations in climate parameters

The mean growing-season temperature (hereafter abbreviated as temperature) is 10.5 °C while the mean open-water-season precipitation (hereafter abbreviated as precipitation) is 459.6 mm for the studied period at Kuopio meteorological station (NORDKLIM). Temperature varies from 7.5 to 13.4 °C and precipitation from 259.0 to 673.0 mm (Fig. 5). Both variables increase towards the present day (Fig. 5).

Climate variables versus BL thickness

Statistically significant ($p < 0.05$) and insignificant ($p \geq 0.05$) correlations were found between temperature and BL thicknesses during 1896–1992 and between precipitation and BL thicknesses during 1895–1992 (Table 3). All the statistically significant correlation coefficients (ρ) are higher than 0.3. In lakes Kuninkaisenlampi, Lehmilampi, and Linnanlampi, statistically significant positive correlations were found between BL thicknesses and climate variables (both temperature and precipitation) whereas in Lake Kantele statistically significant correlation was found only between temperature and BL thickness (Table 3a). Lake Kallio-Kourujärvi shows weak (−0.12 and 0.06) and statistically insignificant correlations between BL thickness and both temperature and precipitation for aforementioned time period. The strongest correlation between BL thickness and precipitation was observed in Lake Lehmilampi record and between BL thickness and temperature in Lake Kantele record (Table 3a).

Examination of shorter-term correlations reveals negative correlation between BL and precipitation during 1896–1973 in Lake Kallio-Kourujärvi and conversely, positive correlation during 1979–1995 (Table 2b). During 1896–1936, correlation with temperature is positive and during 1937–1992 negative in Lake Kallio-Kourujärvi record (Table 3b). The correlations between Lake Kantele BL and precipitation during 1895–1966 and 1975–1995 are negative, but

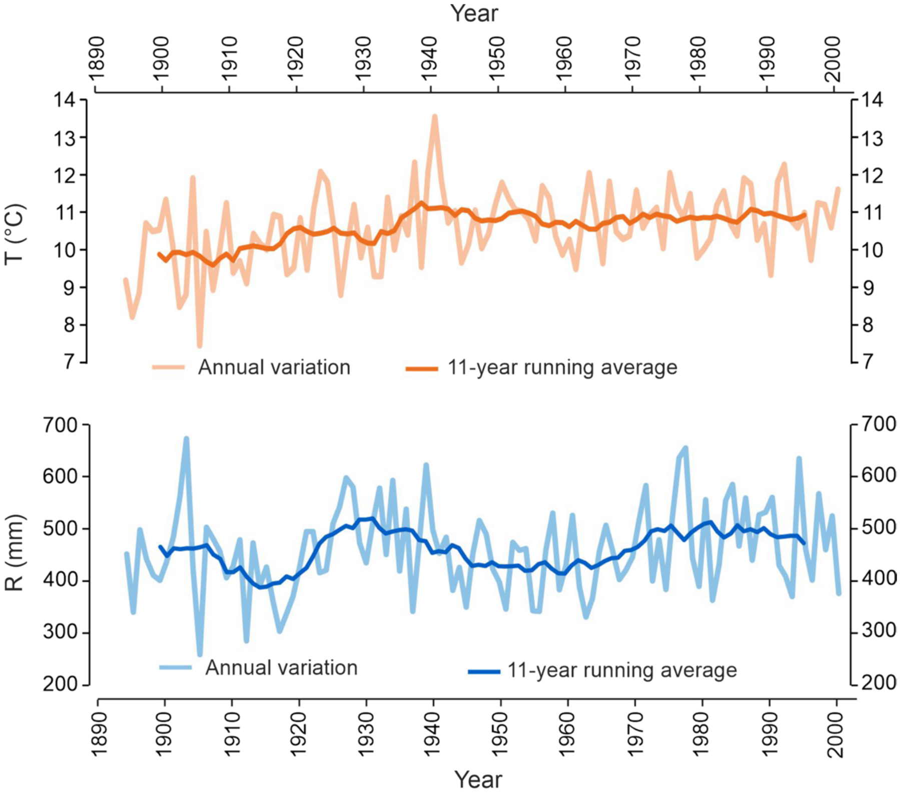


Fig. 5 Growing-season temperature (T) and open-water-season precipitation (R) variability in Kuopio meteorological station during the studied period

Table 3 Correlations between studied climate variables (growing-season temperature (T) and open-water-season precipitation (R)) and BL

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

Period	Variable	ρ	*p*-value
b			
Lake Kallio-Kourujärvi			
1896–1973	R	**− 0.34**	**< 0.01**
1979–1995	R	**0.71**	**< 0.01**
1896–1936	T	**0.43**	**< 0.01**
1937–1992	T	**− 0.36**	**< 0.05**
Lake Kantele			
1895–1966	R	**− 0.34**	**< 0.01**
1975–1995	R	**− 0.52**	**< 0.05**

(a) Correlation coefficients (ρ), *p*-values, and used time periods of monitoring for each lake are provided. (b) Correlations for shorter periods between climate variables and BL thickness of lakes Kallio-Kourujärvi and Kantele records. Statistically significant correlations are shown in bold the correlation coefficient is higher during the latter period (Table 3b).

Discussion

The biogenic component is a crucial part of the varve structure in a variety of varve types from diverse climate zones from middle latitudes up to high arctic (Chutko and Lamoureux 2009; Zolitschka et al. 2015). However, very few studies have evaluated or used the potential of varve biogenic component or its chemical composition as a climate proxy (Sanchini et al. 2020; Zander et al. 2021). The BL thickness is a sum of autochthonous production, transport of allochthonous organic matter as well as degradation. While autochthonous production is controlled by temperature (Kimmel and Groeger 1984; Kelly et al. 2018) and nutrient avalability, the allochthonous organic matter and nutrient transport are expected to be controlled by precipitation (Cohen 2003; Zolitschka et al. 2015). The degradation of organic matter in turn, is controlled by temperature and oxygen availability (Jankowski et al. 2006).

These hypotheses are supported by our correlation analyses between BL thicknesses, and the mean temperature and precipitation of the growing season. Though correlation coefficients between BL thickness and studied climate variables are generally stronger for temperature than for precipitation in the studied lakes, it is not certain that the studied lakes are more sensitive to temperature than precipitation variations. This is because we cannot exclude the influence of anthropogenic actions on BL thickness.

Biogenic lamina thickness and temperature

Aquatic production increases in enhanced temperatures (Kimmel and Groeger 1984; Kelly et al. 2018), and hence positive linear correlation between organic matter accumulation and growing-season temperature is expected. Indeed, strong positive correlations are observed between BL thicknesses and the temperature in the investigated lakes with high trophic status (lakes Kantele, Kuninkaisenlampi, Lehmilampi, and Linnanlampi; Table 3a, Fig. 6). It seems that in these eutrophic lakes, the nutrient availability does not limit the primary production that is enhanced by high temperatures.

Temperature also controls the stability and duration of thermal stratification (Jankowski et al. 2006; Boehrer and Schultze 2008). Warm summers result in strong and prolonged stratification that prevents oxygen transfer into hypolimnion, as Jankowski et al. (2006) observed during the year 2003 European heat wave. Anoxic conditions can enhance the preservation of organic matter but also lead to phosphorus release from the sediment (Mortimer 1941, 1942; Kamp-Nielsen 1975; Spears et al. 2007). In addition, increased oxygen demand due to organic matter degradation following enhanced primary production results in oxygen deficiency in the hypolimnetic waters and promotes phosphorus release. The phosphorus release from anoxic surface sediments may further explain high positive correlations between BL thicknesses and temperature. However, the availability of phosphorus for primary production in anoxia-driven phosphorus release from the deep is not instant, but phosphorus is transferred from hypolimnion to epilimnion mainly during overturns. Therefore, the phosphorous release can influence the nutrient availability during the following year.

The oligotrophic Lake Kallio-Kourujärvi BL reveals a more complex relationship to temperature (Table 3, Fig. 6). There is no statistically significant correlation between temperature and BL thicknesses for long intervals and shorter-term correlations display a period of both positive and negative correlation (Table 3), which have also been observed by Saarni et al. (2015). The negative correlations could result from the limitation of nutrients in a lake of low trophic level. It is possible that during high temperatures, enhanced degradation of organic matter overrides the production rate leading to negative correlation between BL and temperature (Meyers and Lallier-Verges 1999; Gudasz et al. 2010; Saarni et al. 2015). This is supported by the significantly higher temperatures since 1936 at the interval (Fig. 5), where the negative correlation occurs.

Biogenic lamina thickness and precipitation

Enhanced precipitation can have a direct influence on BL thickness through transport of terrigenous organic matter, humic substances, and nutrients into the lake (Zolitschka et al. 2015). Storm-related short-termed high discharge events as well as precipitation from long-lasting and recurrent low-pressure cells can

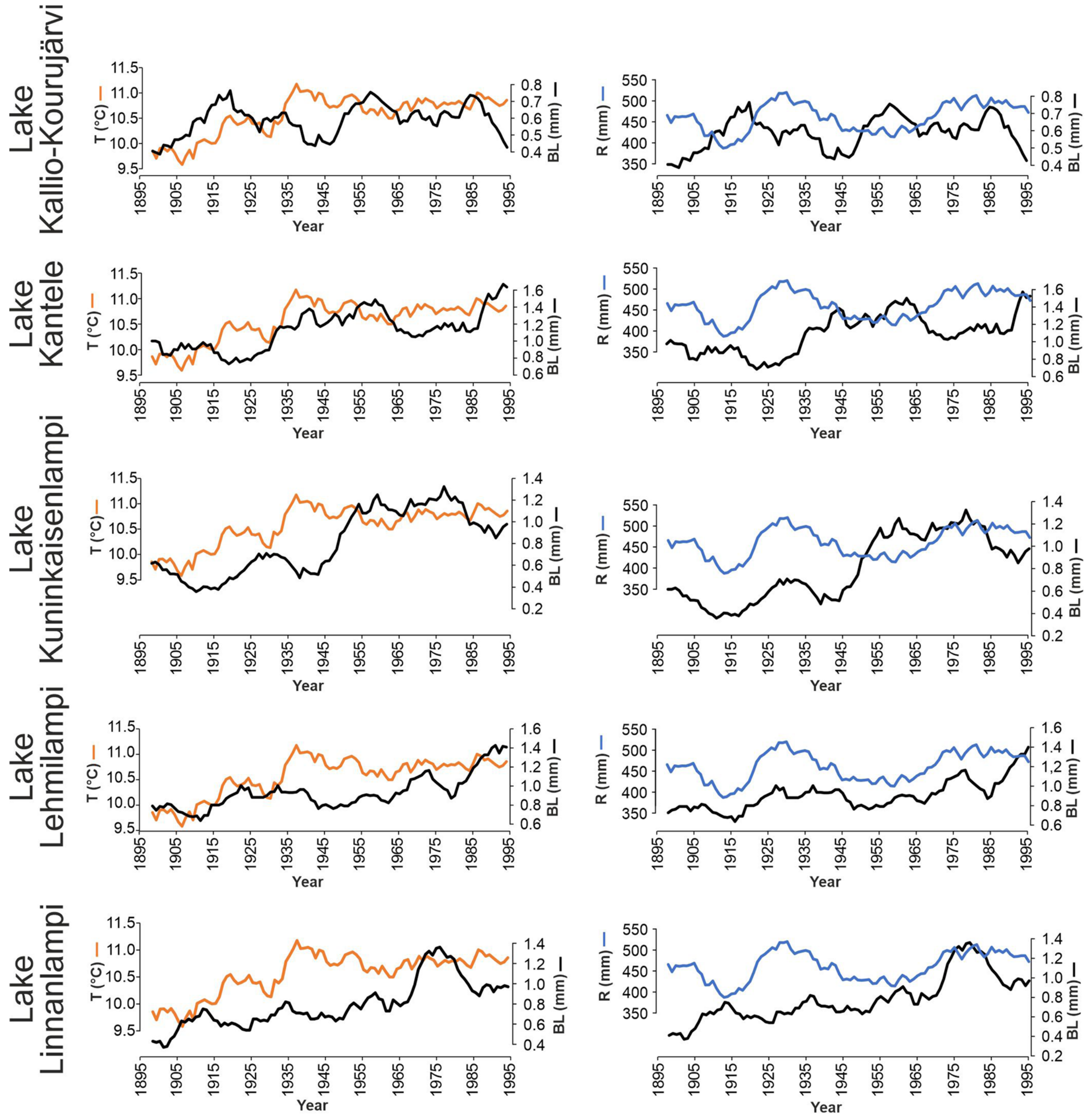


Fig. 6 Variations in 11-year running mean BL thicknesses versus 11-year running mean growing-season temperature (T) and open-water-season precipitation (R) in each lake during the studied period

cause catchment erosion and increased organic and clastic matter transport into a lake through flooding and surface run-off. Furthermore, storm-related wave activity can remobilize organic-rich littoral sediments contributing to increased BL thickness.

The influence of precipitation is manifested in positive correlations in the records of lakes Kuninkaisenlampi, Lehmilampi, and Linnanlampi (Table 3a, Fig. 6). This dependence was expected because precipitation has earlier been shown to influence total varve thickness in boreal lakes (Itkonen and Salonen 1994; Saarni et al. 2015). Even a single heavy rainfall event related to summer thunderstorms or autumn storms has been observed to cause catchment erosion leading to a measurable increase in sedimentation (Johansson et al. 2019). Short-term high discharge events, however, could be under-represented in the running mean precipitation data and thus affect the correlations.

In lakes Kuninkaisenlampi, Lehmilampi, and Linnanlampi, the positive correlation between BL thickness and precipitation is possibly mainly caused by August-November precipitation because precipitation for this period shows concurrent peaks with BL thicknesses of these three lakes (unpublished data). The rainfall at the end of or right after growing season mobilizes significant amounts of terrigenous organic matter produced during the growing season and leads to thicker BL. Itkonen and Salonen (1994) observed similarly that autumn precipitation asserts a strong control on varve thickness. However, it must be kept in mind that the response of a lake to changes in precipitation may be delayed. A change in precipitation in one month can affect the availability of biogenic matter during the next month (Wohlfarth et al. 1998). For instance, nutrient input following a precipitation event can lead to enhanced accumulation of biogenic matter through boosting autochthonous biogenic production with a delay. All of the three lakes with a positive correlation contain fine-grained nutrient-rich soil types in their catchments.

The highest correlation was observed between Lake Lehmilampi BL thickness and precipitation ($\rho = 0.71$) (Table 3a). This could be partly explained by the lack of upstream processes in a headwater lake (Fig. 1). Upstream-water systems and their processes could hinder the direct influence of precipitation on the lake (Horne and Goldman 1994). This is a significant catchment detail, because the contribution of streamflow from upstream lakes is generally considered important even if upstream lakes make up a very small area of the catchment (Leach and Laudon 2019). Lake Lehmilampi is influenced only by surface runoff from the catchment and the river or dredge discharge from the mires. Catchment area to lake-surface-area ratio is also low in Lake Lehmilampi (Table 1), which means that the influence of catchment area on the lake is limited. Furthermore, it has been previously shown that during the past 200 years the variations in the extent of varve preservation in Lake Lehmilampi were controlled by climate rather than human influence (Salminen et al. 2019), which suggests that the lake primarily reflects climatic variations.

Interestingly, Lake Kantele BL shows negative correlation and Lake Kallio-Kourujärvi BL displays both negative and positive correlations to precipitation (Table 3b). These negative correlations are observed most likely because lakes can have different or even inverse responses to climate depending on, for instance, catchment characteristics of the lake, lake morphology, or lake elevation (Fritz 2008; Adrian et al. 2009; Hayes et al. 2017). Catchment characteristics have previously been observed to determine how climate controls the accumulation of clastic material (Saarni et al. 2017) found slightly different positive and negative correlations between BL thickness and open-water season precipitation in Lake Kallio-Kourujärvi. This difference can result from a study period with different length. For reasons that remain unknown, the correlations between CL and hydro-climate parameters are complex in Lake Kantele (Saarni et al. 2017). This seems to be true also for Lake Kantele's BL thickness response to climate parameters. In Lake Kallio-Kourujärvi, the negative correlation could be explained by the low trophic state of the lake and by the outcrop-dominated nutrient-poor coarse-grained catchment that is almost devoid of agricultural land. Thus, only limited amounts of terrigenous organic matter and nutrients are available in the catchment. The change from negative to positive correlation with precipitation starting in the late seventies could be related to peatland drainage during 1973–1988 and introduction of chemical fertilizers in the catchment area. Oxygen profiles of an oligotrophic lake may be regulated primarily by physical mechanisms (Cohen 2003), such as variations in surface runoff and river discharge. In a lake with very limited supply of nutrients and terrestrial organic matter, precipitation-induced high surface runoff and river discharge of well-oxygenated waters may cause overriding of primary production by enhanced degradation of organic matter. Subsequent introduction of chemical fertilizers could have resulted in the turn from negative to positive correlation by enhanced supply of nutrients and increased primary production during periods with high precipitation.

It must also be kept in mind that the distances between the studied lakes and the meteorological station may have resulted in an omission of local short-time weather events from the instrumental records. This is expected to influence more the correlations between BL and precipitation than those to temperature. This is because, for instance, heavy summertime rainstorms can be very local in Finland (FMI database) and thus increase nutrient and organic matter input locally.

Anthropogenic influence

Human actions in lake catchments can weaken or even mask the climate signal (Zolitschka et al. 2003; Salminen et al. 2021) because the signal of anthropogenic impact is usually strong and well-preserved in varve records (Zolitschka et al. 2015). On the other hand, climate signal can also be strengthened by human actions in the lake catchment (Itkonen and Salonen 1994; Bush et al. 2017). Forest cutting, road construction, or rise of mechanical agriculture, for instance, have promoted soil erosion during the studied period (Pekkarinen 2010) and this has also been the case in the catchments of each of the studied lakes. While the release of clastic matter from the lake catchment is promoted by such activities, as discussed earlier by Saarni et al. (2017), organic material is also released. These anthropogenic stressors have been evidenced in Finland as increased varve thickness during the twentieth century (Itkonen and Salonen 1994; Tiljander et al. 2003; Meriläinen et al. 2010; Saarni et al. 2015). Enhanced organic material accumulation is related to slash and burn cultivation already prior to the nineteenth century (Grönlund 1991). During the study period, several human actions were conducted in the catchment of each lake (Table 1; NLS database; Paikkatietoikkuna) and thus BL thickness has increased towards the present day (Fig. 3). The occurrence of occasional CL in the topmost varve structures of Lake Kallio-Kourujärvi biogenic varve record is also related to intensive land use (Saarni et al. 2015).

Forest cutting makes the soil more prone to erosion (Zolitschka 1998; Arnaud et al. 2016) and thus increases allochthonous biogenic matter and nutrient supply into the lake leading to an increase in BL thickness. Forest cutting in the catchment of Lake Kuninkaisenlampi (1939–1994; Table 2; Paikkatietoikkuna) could have induced higher accumulation of organic matter since 1945, while road constructions (1973–1990; Table 2; NLS database) did not cause clear changes in the accumulation of organic matter. In Lake Kantele, forest cutting in the catchment (< 350 m from the lake; 1953–1994; Table 2; NLS database) seems to have increased the organic matter accumulation in the lake, but in Lake Kallio-Kourujärvi the effect of forest cutting (< 350 m from the lake 1988–1994; Table 2; NLS database) is less evident. Forest cutting seems to have also increased the accumulation of organic matter in Lake Linnanlampi and could have intensified the impact of precipitation that was high during the forest cutting (1973–1991; Table 2, Fig. 5; NLS database). Forest cutting can be followed by forest succession, e.g., changes in vegetation combination and species composition with time (Finegan 1984), that slowly changes soil erosion. It must also be kept in mind that no extensive forest cutting was performed in the catchment of Lake Lehmilampi, at least during 1941–1992, which could partly contribute to the high correlation ($\rho = 0.71$) between precipitation and BL thickness of Lake Lehmilampi.

Peatland drainage occurred in the catchment of each studied lake during the investigated period (NLS database; Paikkatietoikkuna) and could thus have enhanced nutrient and biogenic matter leaching from mires/bogs leading to increased BL thickness. In Lake Kallio-Kourujärvi peatland ditching during 1973–1988 could be partly related to the turn from negative to positive correlation of precipitation in the late 1970s (Table 3b). It is also possible that water level regulation, that started in the catchment of Lake Kuninkaisenlampi in 1972 and that of Lake Linnanlampi in 1951 (Marttunen et al. 2002; Vallinkoski et al. 2010), has affected hydrological processes and BL thickness in these two lakes. Variations in lake-level regulation affect the erosion in the littoral zone (Zawiska et al. 2020) and overturn completeness (Boehrer and Schultze 2008). In addition, the use of chemical fertilizers in agricultural fields since the mid-twentieth century enhanced nutrient and biogenic matter leaching to the lake which could further explain the change in correlation between BL and precipitation from negative to positive at Lake Kallio-Kourujärvi.

According to our results, each lake reflects variations in temperature and precipitation, although anthropogenic actions could have weakened or even changed the correlation at some point of the study period. In addition, severe anthropogenic eutrophication can limit the use of biogenic component thickness as a proxy in climate reconstructions. It would be beneficial if we could link the anthropogenic activities with variations in BL thicknesses or, for instance, the changes in correlation direction of Lake Kallio-Kourujärvi and strengthening of the climate signal in Lake Kantele. However, because the absolute timing (year) of specific human actions in the studied lake catchments is not known, direct temporal influence of each action on BL thickness remains speculative.

Conclusions

We investigated the importance of growing-season temperature and open-water-season precipitation on BL formation in five Finnish lakes. Statistical analyses revealed that BL thickness in the studied lakes generally responded to variations in climate during the study period. Positive correlations between BL thickness and growing season temperature were found for lakes with high trophic status. Positive correlation with open-water-season precipitation was found for lakes with fine-grained nutrient-rich soil types. While the eutrophic lakes showed consistent relationship between BL and climate parameters, the oligotrophic lake with coarse-grained catchment soils showed more complex correlations.

The results show that growing-season temperature and open-water-season precipitation partly control variations in BL thickness. Generally, warmer growing seasons intensify primary production in lakes and their catchments and result in increased amounts of biogenic matter and thicker BL. Open-water-season precipitation controls the amount of allochthonous biogenic material and nutrients transported to the lake and thus influence BL thickness. Though multiple human actions, such as forest clearcutting and bog drainage, have occurred in the catchment of the studied lakes, climate signal on BL thickness is still detectable.

We observed that variations in BL thicknesses in the studied lakes reflect growing-season temperature and open-water-season precipitation. We also emphasize that variations in BL thickness of the studied lakes are sensitive to growing season and open-water season climate. However, more detailed examination is needed to fully understand the relationship between climate and BL thickness.

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Author contributions SS wrote the main manuscript text and prepared the figures. TS, SS, and SS performed the sediment sampling. SS and SS did the laboratory work. Data processing was done by SS and SS. All authors reviewed the manuscript.

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Declarations

Conflict of interest We declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper. The results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration by another publisher. We have read the Springer journal policies on author responsibilities and submit this manuscript in accordance with those policies. All of the material is owned by the authors and/or no permissions are required.

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