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Holocene lake-level evolution of Lake Tiefer See, NE Germany, caused by climate and land cover changes

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Lake-level reconstructions are a key tool in hydro-climate reconstructions, based on the assumption that lake-level changes primarily reflect climatic changes. Although it is known that land cover changes can affect evapotranspiration and groundwater formation, this factor commonly receives little attention in the interpretation of past lake-level changes. To address this issue in more detail, we explore the effects of land cover change on Holocene lake-level fluctuations in Lake Tiefer See in the lowlands of northeastern Germany. We reconstruct lake-level changes based on the analysis of 28 sediment records from different water depths and from the shore. We compare the results with land cover changes inferred from pollen data. We also apply hydrological modelling to quantify effects of land cover change on evapotranspiration and the lake level. Our reconstruction shows an overall lake-level amplitude of about 10 m during the Holocene, with the highest fluctuations during the Early and Late Holocene. Only smaller fluctuations during the Middle Holocene can unambiguously be attributed to climatic fluctuations because the land cover was stable during that period. Fluctuations during the Early and Late Holocene are at least partly related to changes in natural and anthropogenic land cover. For several intervals the reconstructed lake-level changes agree well with variations in modelled groundwater recharge inferred from land cover changes. In general, the observed amplitudes of lake-level fluctuations are larger than expected from climatic changes alone and thus underline that land cover changes in lake catchments must be considered in climatic interpretations of past lake-level fluctuations.

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Climate reconstructions help to better understand the climate system and hence improve projections of future climate change. In the terrestrial realm, climate reconstructions focus on temperature variables, as a wide range of biotic and abiotic proxies respond to temperatures directly, e.g. chironomid larvae, oxygen stable isotopes and membrane lipids (GDGTs, e.g. Stuiver 1970; Walker *et al*. 1991; von Grafenstein *et al*. 1999; Leng & Marshall 2004; Blaga *et al*. 2010). Other proxies provide a direct link to changes in precipitation, e.g. stable oxygen isotopes in speleothems (Affolter *et al*. 2015) or in *Sphagnum* mosses (Kühl & Moschen 2012) and δ^2H values in sedimentary lipid biomarkers (Rach *et al*. 2017). Reconstructions of hydro-climatic changes, which at least in the temperate-humid zone are equally if not more important than temperature variations, are commonly based on water level reconstructions from lakes or peatlands.

For lake-level reconstructions, two main strategies exist. The more established strategy is using indicator sediment layers from the lake shore, such as peat or lacustrine sand layers (Digerfeldt 1986; Magny 1992; Dearing 1997). The approach is accurate in terms of absolute past lake levels but may provide low temporal resolution. Also, gaps in the reconstruction may appear when evidence is missing for some periods. Lake-level reconstructions may alternatively be based on lake bottom sediments, which commonly provide a continuous record for potentially high-resolution reconstructions (e.g. Pleskot *et al*. 2018). However, linking lake bottom sediment composition to past lake-levels is far from trivial because sediment composition is influenced by numerous factors, not only by water depth (e.g. Magny *et al*. 2007; Dietze *et al*. 2016).

A further challenge is to interpret reconstructed lake-level variations in terms of hydro-climatic dynam-

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ics because lake-level variations may be related to other factors as well. Those factors may be natural, e.g. beaver dams or landslides, or artificial, e.g. the construction of dams or drainages. Also, von Humboldt (2000) suggested that lake levels have been affected by land use intensity since more than 2000 years ago. He hypothesized that the rapid lake-level lowering in tropical Lake Valencia (Venezuela) is the result of intense land use and deforestation in the catchment area. More recent studies support this hypothesis by showing that the lake-level trend reversed during the South American wars of independence, when land use intensity was reduced (Crist & Chardon 1941). Bradbury *et al.* (1981) also argue that the very rapid modern lake-level lowering cannot be explained by climatic fluctuations alone.

The land cover may influence lake-levels because it affects evapotranspiration, a key element of the water budget. In central Europe, for example, evapotranspiration in coniferous forests is significantly higher than evapotranspiration in broad-leaved forests or open vegetation (Bosch & Hewlett 1982; Peel *et al.* 2010; Müller 2011; Gan *et al.* 2021). Therefore, forest conversion is well recognized as a measure to stabilize and increase groundwater recharge (Lasch *et al.* 2012). Natkhin *et al.* (2012) and Kaiser *et al.* (2014a) show that changes in forest structure and climate effects are equally important drivers for recent lake-level variations in northeastern Germany. Also other studies from that region discuss that climatic and non-climatic factors, including land cover changes, contribute to lake-level variations (Kaiser *et al.* 2012; Dietze *et al.* 2016). Similarly, studies from northern Poland discuss the more complex impact of land use intensity on peatlands (e.g. Lamentowicz *et al.* 2020).

Nevertheless, the impact of the land cover is often given limited attention and past lake-level variations are commonly attributed to climatic factors (e.g. Magny *et al.* 2011). We here hypothesize that besides the climate, changes in land cover and land use have influenced lakes in the study region during the Holocene. To test this hypothesis, we (i) reconstruct Holocene water level changes in Lake Tiefer See, northeastern Germany, by combining analysis of profiles from the shallow water, adjacent peatlands and an exposed lake terrace; (ii) produce high-resolution land cover reconstructions for the catchment area of the lake; (iii) compare lake-level variations with reconstructed land cover changes and known climate variations; and (iv) test potential effects of land cover changes using water balance modelling. The final goal is to estimate the impact of land cover changes on the lake-level for a better understanding and interpretation of past lake-level changes.

Material and methods

Study site

Lake Tiefer See (latitude 53°35′36″N, longitude 12°31′46″E, Fig. 1) is a deep (62 m), medium-sized (~0.75 km²) lake in the young morainic lowlands of northeastern Germany. The lake is part of the Klocksin Lake chain, which formed as a deep subglacial meltwater channel crossing a terminal moraine of the Pomeranian Phase of the Weichselian glaciation. Today, the lake has a narrow permanent connection with Lake Hofsee to the south and intermittently receives inflow from Lake Flacher See to the north. The setting likely changed through time depending on the lake level and particularly after the construction of a railroad dam between Flacher See and Tiefer See in 1884–1886. A 35-year gauging record from the adjacent Lake Hofsee shows high annual fluctuations, with minima during autumn and maxima during spring. The amplitude of annual fluctuations is mostly between 40–60 cm, in some years up to 1 m (State Agency for Agriculture and the Environment Mecklenburg Lake District). The surface catchment area of Lake Tiefer See comprises ~5.5 km² mainly of glacial till (Kienel *et al.* 2013; State Agency for Environment, Nature Protection and Geology Mecklenburg-Vorpommern). The catchment of the lake is mostly used for arable farming (~90%), and pine forests occur ~2 km west of the lake. The lake is surrounded by a fringe of mixed deciduous trees and shrubs, including alder carrs to the west and east (Fig. 1). Mean monthly temperatures range from 0 °C in January to 18 °C in June, the mean annual temperature is 8.1 °C. Mean annual precipitation at the nearby weather station of Waren (Müritz) for the period 1980–2020 is 591 mm (www.dwd.de).

Lake Tiefer See is mostly surrounded by a lake terrace that ranges from a few decimetres to ~1.5 m above the mean lake level, roughly corresponding with the 65-m NHN (~m a.s.l.) contour line. The terrace extends into adjacent, peat filled basins. Partly, the terrace is followed by a steep inactive and up to 10 m high cliff.

Lake marginal sediments

To reconstruct Holocene lake-level variations, we use 25 sediment cores from the lake margins and six profiles from the 65-m NHN terrace (Table S1). Six of the sediment cores were retrieved from surrounding peatlands, 19 from the shallow water, either from the ice or raft. Most lake cores were taken with a piston-corer (ø 8 cm), the peat cores mainly with a Russian type corer (ø 7 cm).

Lake marginal cores were mostly sampled at 10-cm intervals. Samples were air-dried, ground and homogenized in a mortar. Organic matter content was estimated

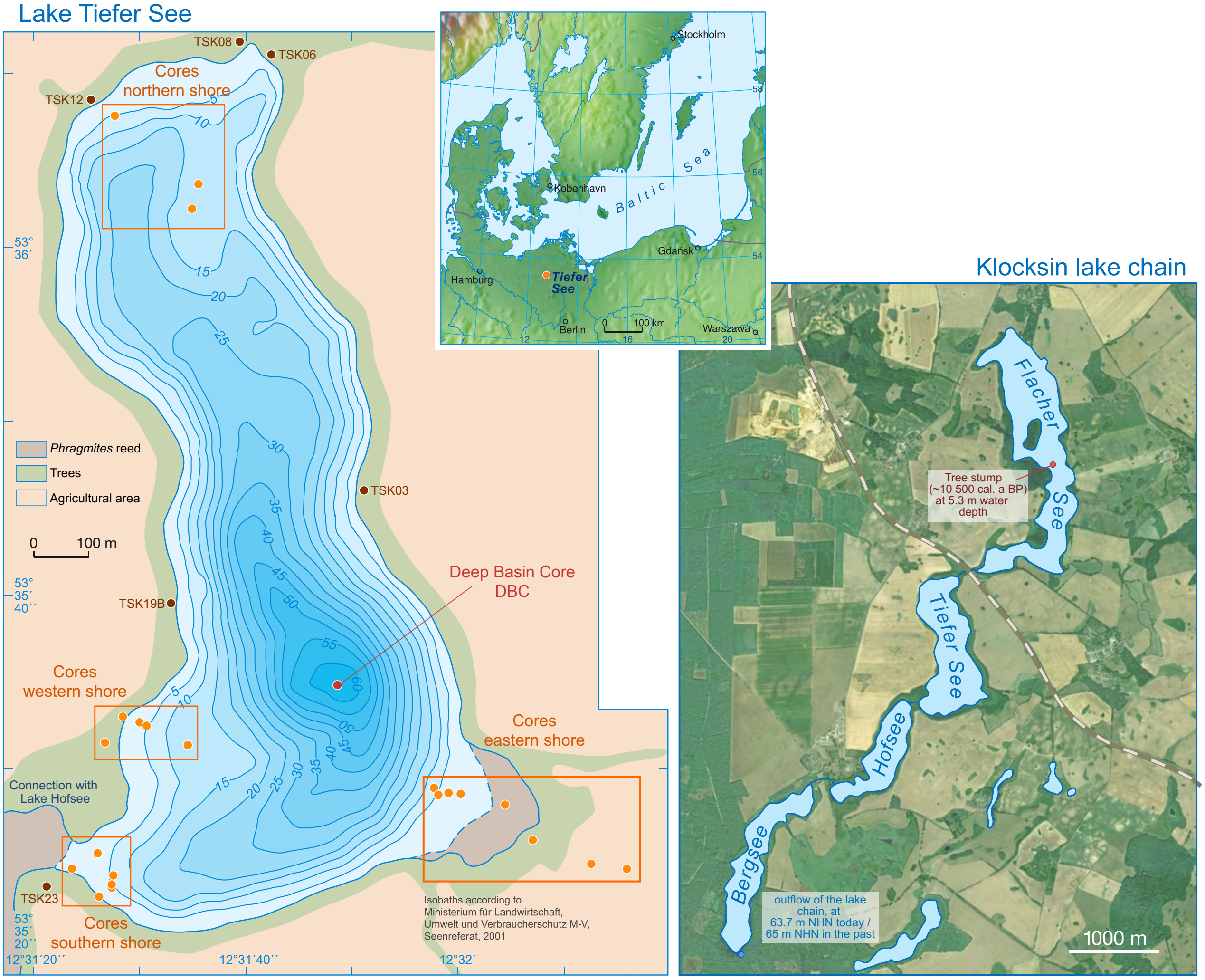

Fig. 1. Topographic map of Lake Tiefer See, with location of coring sites (orange) and soil profiles (brown).

by loss-on-ignition (LOI) at 550 °C for 2 h. Carbonate content was estimated using the Scheibler method. Grain-size distribution was determined by a FRITSCH Analysette 22 Microtec laser particle sizer in a range of 0.08–2000 μm.

Lake marginal cores were sampled for microfossil analysis at 10-cm intervals, or less when needed. Preparation of the 1-cm³ samples (cf. Fægri & Iversen 1989) included treatment with HCl, 20% KOH, sieving (120 μm) and acetolysis (7 min). Lycopodium tablets (Lund University, Batch 1031 and 3862) were added to estimate pollen concentrations (Stockmarr 1971). Samples were mounted in glycerine and counted at 400× magnification or 1000× magnification for critical pollen grains. Pollen identification mostly follows Moore *et al.* (1991) and Beug (2004), indicated with suffix (m) and (b) added to the pollen type names, respectively. Cerealia pollen grains were separated as Secale cereale, Hordeum group, Avena-Triticum group (Moore *et al.* 1991), or as Cerealia undiff. With some exceptions, pollen samples were counted until an upland pollen sum of at least 300. To differentiate between plant taxa and pollen types in the text, the latter are displayed in small capitals (cf. Joosten & de Klerk 2002).

We use macrofossil analysis to reconstruct local vegetation and habitats to infer water levels. We studied the three long peat sequences in TS-2, TS-3 and TS-17 and several short peat sections. Samples (~2–3 cm thick, 25 cm³ in TS2 and TS3, 50 cm³ in TS17) were taken mostly at 10-cm intervals, or less when needed. Samples were boiled in 5% KOH for 5 min, and sieved at 1.0, 0.5 and 0.25 mm mesh sizes. Each fraction was scanned using a Zeiss Stereomicroscope with up to ×40 magnification. When necessary, remnants were identified with a Zeiss Axiolab microscope at ×100–400 magnification. Macrofossil identification follows Matjuschenko (1924), Katz & Katz (1933), 1977, Beijerinck (1947), Körber-Grohne (1964), Katz *et al.* (1965), Nilsson & Hjelmqist (1967), Grosse-Brauckmann (1972), Schoch *et al.* (1988), Frahm & Frey (1992), Grosse-Brauckmann & Streitz (1992) and

Table 1. Interpretation of cores and macrofossil data in terms of vegetation type and water level. Water level classes were attributed to vegetation units following Succow & Joosten (2001).

Sediment type and indicators	Reconstructed habitat	Water level class	Corresponding water level limits (cm)
Peat with above *and* below ground remnants of trees	Forest (mainly alder carr)	5+	–10 to +10
Peat mainly with remnants of reed plants (including *Eupatorium canabinum*, *Thelypteris palustris*, *Urtica dioica*), aquatic remnants may be present	Semi-aquatic reed	6+/5+	–10 to +100
Peat with abundant aquatic remnants from aquatic plants (e.g. *Nymphaea* and *Potamogeton* endocarps), aquatic animals (*Christatella mucedo*) and reed plants	Aquatic reed	6+	+10 to +100
Peat with mainly aquatic remnants and rare above ground remnants of terrestrial plants	Lake phase		>+50
Gyttja (organic or calcareous)	Lake phase		>+50

Michaelis (2001). Diaspores were counted while the amount of tissues was estimated as the per cent of total subsample volume. To interpret macrofossil data in terms of water levels, we translate inferred local vegetation into local water levels using the water level classification from Succow & Joosten (2001) (Table 1).

Age-depth modelling

Age-depth models of most cores are based on pollen stratigraphy, i.e. by correlation with the reference profile DBC from the deep basin of Lake Tiefer See (Dräger *et al.* 2017). Pollen stratigraphical dating is feasible because of the short distance to the reference profile, which is well dated by varve counts, 13 AMS radiocarbon dates and eight cryptotephras (Wulf *et al.* 2016; Dräger *et al.* 2017). During the Late Holocene it includes numerous prominent changes in pollen composition, which allow accurate correlation. Long peat sections and basal peat layers have been radiocarbon dated (Table 2). Age-depth models were produced with BACON in R (Blaauw & Christen 2019, R core team 2020).

Sedimentology and geochronology of the dry lake terraces

From the terraces and lower slopes around Lake Tiefer See, 24 auger cores (3 m deep) were taken. Moreover, six soil pits were documented following Ad-hoc-AG Boden (2005) and sampled for geochemical analysis (n = 77; Fig. 1, Data S2). Samples were air dried and hand-crushed. Humus and carbonate, when present, were removed by 30% H_2O_2 and 10% HCl, respectively. Grain sizes were estimated by laser diffraction (HORIBA partica LA-950V2). Total organic carbon (TOC) was measured by elemental carbon analysis (HEKAtech Euro EA-CHNSO). $CaCO_3$ content was estimated as total inorganic carbon (TIC), i.e. as total carbon minus total organic carbon (TOC). Eight samples (six from lacustrine sediments, two from colluvial sediments) from three sites were dated using optically stimulated luminescence (OSL) dating at Humboldt University Berlin (Data S2). Dating followed standards of the Berlin laboratory, using the sand-size sediment fraction of 90 to 200 μm (coarse grain technique, Preusser *et al.* 2008). The OSL ages are reported as years (a) with the year of measurement as reference year (2016), as the term BP is reserved for radiocarbon ages (Brauer *et al.* 2014).

Hydroacoustic survey

A hydroacoustic (bathymetry and backscatter intensity) and seismic survey was carried out on 27th June 2017. Hydroacoustic data were acquired using a portable Norbit iWBMSe system operating at a centre frequency of 400 kHz with 80-kHz bandwidth and a frequency-modulated signal shape. Navigation data were provided by a POSMV Seastar system utilizing the EGNOS correction for a navigational accuracy of 40–50 cm in each direction. Side-scan sonar-like maps of backscatter intensity were generated from the beam time series (snippets) of the multibeam echo-sounder. Processing was done using the software Hypack 2017, and involved application of a patch test, correction for sound velocity profiles and removal of outliers. All backscatter intensities represent relative values; therefore, no dB values are provided (Lamarche & Lurton 2018).

Constructing the lake-level curve

Primarily we infer past lake-levels from the type of deposit in littoral, peatland and terrace profiles. We assume that gyttja indicates a water depth of 0.5 m or more. Peat typically forms with the water level near the surface, yet there may be some variations represented in on-site vegetation. Peat sections may also include transformed gyttja layers. To refine interpretation of peat we employ micro- and macrofossil analysis (Table 1). Based on the resulting information we for each core compile

Table 2. Radiocarbon dates.

Core	Depth (m)	Lab. code	Material	Dry weight	^{14}C age (a BP)	1δ range (cal. a BP), probability
TS-00	2.09–2.10	Poz-62025	*Carex* nuts, charred material	2.05 g	3420±40	3614–3719, 0.96
TS-1	0.71–0.74	Poz-83790	Leaf fragments, *Betula* nuts, bud scales	2.6 mg	1185±30	1065–1142, 0.90 1160–1169, 0.10
TS-1	1.12–1.15	Poz-83791	Leaf fragments, *Betula* nuts, bud scales	2.1 mg	1640±35	1423–1431, 0.05 1442–1458, 0.10 1115–1571, 0.71 1582–1601, 0.13
TS-2 2013	1.62–1.63	Poz-60077	*Betula* nuts, *Alnus* nuts, bud scales, *Schoenoplectus* fruit	2.38 mg	905±30	778–803, 0.24 809–830, 0.22 855–905, 0.55
TS-2 2012	1.53–1.54	Poz-60078	*Carex* nuts, *Betula* nuts, *Urtica* fruits, *Schoenoplectus* fruit, leaf	2.2 mg	3200±30	3391–3445, 1
TS-2 2012	2.58–2.60	Poz-60079	Charcoal	2.25 mg	7420±40	8189–8220, 0.29 8236–8310, 0.71
TS-2 2012	3.78–3.82	Poz-60080	*Carex* nuts, *Betula* nuts, *Schoenoplectus* fruit, leaf, bud scale	1.79 mg	2975±30	2973–3075, 1
TS-2 2012	4.315–4.33	Poz-60081	*Phragmites* leaves + stem basis	17.5 mg	8130±40	9010–9091, 0.92 9107–9116, 0.08
TS-2 2012	3.77–3.80	Poz-68592	*Betula* nuts, *Carex* nuts	2.1 mg	2975±30	3080–3094, 0.12 3107–3128, 0.17 3139–3212, 0.70
TS-2 2012	2.34–2.37	Poz-68591	*Cladium* fruits	4.1 mg	7910±30	8637–8770, 1
TS-3 2014	2.41–2.42	Poz-83789	*Carex* nuts, *Urtica dioica* nut, seeds of *Eupatorium*, *Cyperus fuscus*, *Typha*, *Juncus*, Caryophyllaceae, *Alisma plantago-aquatica* embryo	2.6 mg	3920±35	4296–4331, 0.33 4349–4420, 0.66
TS-3 2014	3.20–3.21	Poz-83788	*Populus* bud scale	8.0 mg	6170±40	7012–7129, 0.91 7146–7157, 0.09
TS-3 2014	3.39–3.40	Poz-68593	*Cladium* fruit, *Alnus* nuts, *Carex lasiocarpa* nuts	2.3 mg	6665±35	7509–7544, 0.63 7555–7577, 0.37
TS-6	0.40	Poz-62030	Bud scale, leaf nodes, charred material	0.8 mg C	11 310±70	13 129–13 249, 1
TS-15	5.83–5.85	Poz-62036	*Betula* bud and fruit scales		9960±60	11 261–11 409, 0.69 11 434–11 477, 0.14 11 487–11 491, 0.01 11 552–11 600, 0.16
TS-17	2.50	Poz-74945	*Carex* nuts, *Betula* nuts, bud scales	3.0 mg	3100±30	3267–3290, 0.29 3323–3368, 0.71
TS-17	3.50	Poz-74946	*Carex* nuts, *Betula* nuts, *Lycopus* seeds	2.1 mg	5175±30	5910–5941, 0.80 5973–5984, 0.20
TS-17	4.50	Poz-74947	*Carex* nuts, *Betula* nuts, *Alnus* nuts	4.3 mg	5975±35	6749–6765, 0.15 6775–6806, 0.34 6812–6856, 0.50
TS-17	5.30	Poz-74948	*Carex* nuts, *Betula* nuts, further seeds and bud scales	2.8 mg	7280±40	8033–8063, 0.26 8085–8161, 0.74
Lake Flacher See 53°36′53″N 12°32′34′E	5.60	Poz-132064	Wood of tree stump		9330±50	10 693–10 378, 0.94

inferred lake-levels in ~100-year intervals. We finally overlay results to infer the most probable Holocene lake-level curve.

Reconstructing catchment vegetation

To infer past vegetation composition on the different soil types occurring in the Lake Tiefer See catchment we use the extended downscaling approach (EDA; Theuerkauf & Couwenberg 2017). EDA requires numerous pollen records from a region; we here apply it with pollen data from in total 53 pollen records from northeastern Germany (Table 3, Fig. S1). We selected sites with prevailing atmospheric pollen deposition, i.e. medium-sized to large lakes with circular shape and no major inflow. For each record we summed up (if present) pollen data from six distinct and well-detectable time slices: the Early Holocene Betula period (around 11 550–11 450 cal. a BP), the Early Holocene Pinus period (around 11 200–10 800 cal. a BP), the Middle Holocene forest period (8000–6000 cal. a BP), the Bronze Age settlement period (4000–3000 cal. a BP), the Migration Period (1550–1350 cal. a BP) and the Medieval Period (750–650 cal. a BP).

The EDA furthermore requires landscape data. We here focus on soils, which primarily determine vegetation

Table 3. Pollen records used for EDA analysis, with the number of samples summarized for each time slice.

Site	Early Holocene Betula period	Early Holocene Pinus period	Middle Holocene	Bronze Age	Migration Period	Medieval Period	Reference/data contributor
Ahlbecker Seegrund		6					Fukarek in de Klerk (2005)
Amtssee Chorin	3	2	10		4		Schoknecht (unpubl.)
Bixbeerenbruch		3					Müller (1962)
Byhlegurer Bagen		3					Strahl (2005)
Carwitzer See			2	3	4	1	Mrotzek (2017)
Diebelsee	1	2					Schlaak & Schoknecht (2002)
Drewitzer See	2	2	6	4	4	2	Schult (unpubl.)
Dudinghauser See				3	2	4	Dörfler in Dreßler *et al.* (2006)
Felchowsee	2	2					Jahns (2000)
Gabelsee	6						Jahns (unpubl.)
Gadowsee				3	3	1	Theuerkauf (unpubl.)
Galenbecker See Rinne					3	4	Fukarek in de Klerk (2004)
Gorinsee	2	1					Theuerkauf (unpubl.)
Groß Radener Binnensee		2	4	5	2	3	Jeschke & Lange (1987)
Groß Rehberg	2	4					Schoknecht (1996)
Großer Serrahnsee	3	4	2	3	3	3	Müller (1962)
Heinrichswalder Damm	4	5					Fukarek in de Klerk (2004)
Hoher Birkengraben	10	10					de Klerk (2002)
Hüttendamm	4	2					Fukarek in de Klerk (2004)
Kargowseen	3	4	4	2	4	2	Schoknecht (1996)
Kieshofer Moor	2	2	4		3		Theuerkauf (unpubl.)
Klädener Plage	2	3					Theuerkauf (unpubl.)
Kleiner Fauler See	3	3					Herking (2002)
Klinker Plage	3	3					Theuerkauf (unpubl.)
Löddigsee	2	7	17	5	2	3	Jahns (2007)
Moor am Schwarzen See	3						Müller (1962)
Moorer Busch	2	3					Fukarek in de Klerk (2007)
Moosbruch	5	5					Fukarek in de Klerk (2004)
Neubrück	5	3					Müller (1962)
Neu Heinder See				2	2	5	Theuerkauf (unpubl.)
Pelsiner See			5	3	3	4	Theuerkauf (unpubl.)
Plasterinsee	2						Müller (1962)
Postbruch III	3	3					Müller (1962)
Potremser Moor	2	3					Theuerkauf *et al.* (2014)
Rugensee			2	4	2	2	Dörfler (2011)
Schönwolder Moor	2	3					Theuerkauf (unpubl.)
Schulzensee (Dörfler)	2	2					Dörfler in Schwarz (2006)
Schulzensee Zechow	1	3	11		2		Schoknecht in Gärtner (1998)
Serrahn 112	1	3					Müller (1962)
Starvitzer See			8	4	5	3	Schoknecht (1996)
Stassower See						2	Theuerkauf (unpubl.)
Stinthorst		8					Schoknecht (1996)
Tangahnsee			2	3	2	2	Theuerkauf (unpubl.)
Tessiner See				4	2	2	Theuerkauf (unpubl.)
Teufelsbruch	1	3					Müller (1962)
Teufelsmoor am Schwarzen See	2						Müller (1962)
Tiefer See (Demen)	2	3	5	3	4	2	Dörfler in Schwarz (2006)
Tiefer See (Klocksin)			7		5	4	Dräger *et al.* (2017)
Tollensetal Trollenhagen	2	3					Kloss (unpubl.)
Vielbecker See			11	4	4	3	Dörfler (unpubl.)
Waldsee	2	2					Müller (1962)
Wedendorfer See			1	3	3	2	Theuerkauf (unpubl.)
Weißes Moor	3	3					Theuerkauf (unpubl.)

patterns in the study region. For each site, we extracted the cover of major soil and substrate types in concentric rings from 0.1- to 50-km radius from the digital soil map BÜK200 (1:200 000, Ad-hoc-AG Boden 2005). Soil classification follows IUSS Working Group WRB (2015).

EDA was applied with 'edar' from the 'disqover' R package with 'LSM unstable' as the distance weighting option and PPEs from PPE.MV 2015 (Theuerkauf *et al.* 2015, R core team 2020). These PPEs were produced with a state-of-art Lagrangian stochastic dispersal model (LSM) in the study region itself and from similar sites. They are hence the most suitable PPEs. The EDA produces mean plant abundances on the various soil types/soil substrates in the landscape, from which we calculated mean vegetation composition in the catchment area of Lake Tiefer See.

The pollen record from the deep basin is translated into past vegetation composition with ROPES (Theuerkauf & Couwenberg 2018). Unlike REVEALS (Sugita 2007), ROPES does not require PPEs as an input parameter. It hence avoids the assumption that PPEs, which represent present-day pollen productivity, represent pollen productivity in the past. ROPES was applied with the 'LSM unstable' dispersal model option, the extent of the region set to 100 km and a maximum number of 10 000 iterations.

Water balance modelling

Vegetation influences evapotranspiration (ET) and thus groundwater recharge by interception and root water uptake. Both depend on species-specific plant characteristics, e.g. leaf area index (LAI), rooting depth, surface roughness and stomata control. ET is likely higher in forests than for grassland or crops (Zhang *et al.* 2001; Peel *et al.* 2010), most likely due to deeper roots and a higher LAI.

Our hydrological modelling is based on a simple water balance with the following assumptions: (i) soil moisture storage is at steady-state and changes in ET directly affect groundwater recharge; (ii) surface runoff is neglected (most water not subject to ET ends up in the subsurface because of the flat relief of the study region); (iii) today's climate serves as the basis with which to estimate the influence of land cover changes; and (iv) only land cover is changing, climate is kept constant.

Based on today's climate we use the equation proposed by Zhang *et al.* (2001):

$$\frac{\mathrm{ET}}{\mathrm{P}} = \frac{1 + \mathrm{w}\frac{\mathrm{E_0}}{\mathrm{P}}}{1 + \mathrm{w}\frac{\mathrm{E_0}}{\mathrm{P}} + \left(\frac{\mathrm{E_0}}{\mathrm{P}}\right)^{-1}} \tag{1}$$

with actual evapotranspiration ET (mm), annual precipitation P (mm), potential ET E_0 (determined with Hargreaves equation, Aguilar & Polo 2011) and plant available water coefficient w (depends mainly on rooting depth). We used $w = 2$ for forests and $w = 0.5$ for grassland and crops (Zhang *et al.* 2001). We calculated precipitation as the 30-year mean and E_0 as the 10-year mean based on data from the DWD meteorological station Waren (Müritz).

For catchments with mixed land use we then apply (Zhang *et al.* 2001):

$$\mathrm{ET} = \mathrm{fET_f} + (1 - \mathrm{f})\mathrm{ET_h} \tag{2}$$

with total annual evapotranspiration ET (mm), fraction of forest cover f, annual ET from a forest ET_f (mm), and annual ET from herbaceous vegetation ET_h (mm).

To determine the newly developing steady-state groundwater level, the model was combined with an outflow function following Darcy's Law. Based on groundwater level observations at the nearby Klocksin well, today's outflow is estimated as 120 mm a^{-1} and this is used as the initial outflow value. The initial gradient is roughly estimated as 0.0013 m m^{-1} (from the state hydrogeological map), the initial height of the water column is set to 10 m and porosity to 30%.

To test the sensitivity of the response and account for the uncertainties in parameters we repeated the calculations with a groundwater outflow of 150 mm a^{-1} and an initial height of the water column of 20 m. In total, we calculated four groundwater levels for each time slice.

Results

Acoustic data

Acoustic data (Fig. 2) confirm a lake depth from 30 m in the northern to >60 m in the southern basin. Two ridges of glacial till protrude from the north and southwest. High backscatter intensities (Fig. 2) indicate more consolidated and/or coarser grained sediments on these ridges. TS-12 (western ridge) and TS-18, TS-19 (northern ridge) confirm presence of only a thin gyttja layer (<20 cm) above glacial sediments, indicating that gyttja deposition on the ridges is likely hampered by internal currents.

Our main discovery is a structure at approx. 8–9 m below modern lake level and all around the lake, which we interpret as a former lake terrace (Fig. 2). Along the terrace, we frequently observe small-scale landslide deposits with exposed boulders. At the eastern shore, backscatter data also indicate deposits of a known landslide from summer 2011. Surface sediment cores show that the landslide deposited mm- to cm-scale mixed event layers of fine detrital sand and reworked littoral deposits.

Interpretation of lake-level dynamics

Lateglacial. – The onset of limnic deposition in the deep basin at around 13 000 cal. a BP indicates that dead ice remained in the basin during most of the Lateglacial (Data S1). Limnic deposition in cores from the western (TS-14, TS-15 and TS-17) and northern (TS-11) shores only starts in the Early Holocene, suggesting that locally dead-ice melting was further delayed. Such late dead-ice melting is reported also from the neighbouring Lake Hofsee (Homann *et al.* 2002) and other lakes in north-eastern Germany (e.g. Kaiser *et al.* 2012, 2018a) and Poland (Błaszkiewicz *et al.* 2015).

Early Holocene (11 600–9000 cal. a BP). – The Early Holocene period is, at least partly, covered in eight lake

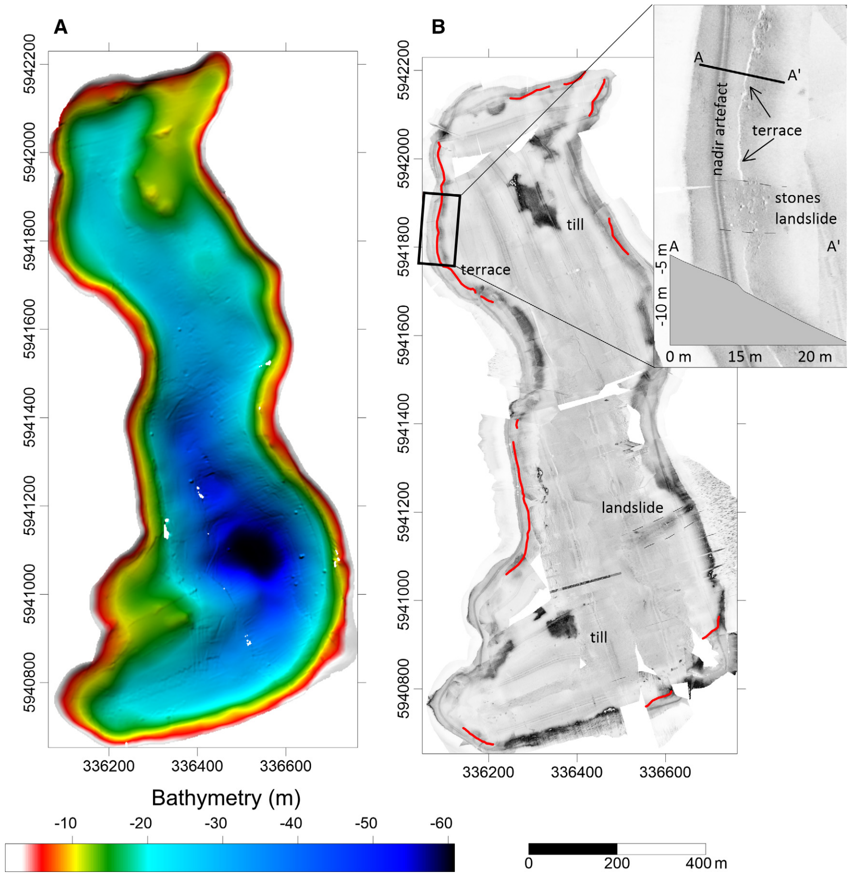

Fig. 2. A. Bathymetric map of Lake Tiefer See. B. Map of surface backscatter intensity, with dark spots indicating high intensities. The inset in detail shows the terrace that is detectable around the lake. It is recognized by reduced backscatter intensities, i.e. an acoustic shadow, indicated by brighter colours. This effect is caused by the morphological step formed by the terrace and the locally increased slope angles. Coordinates in UTM33, WGS84.

marginal cores. Deposition of calcareous gyttja in TS-0 at −2.6 m indicates that the lake level was high, possibly near to modern values, after the Younger Dryas - Holocene transition, possibly temporarily near to modern values (Fig. 3). Between 11 000 and 10 000 cal. a BP, the lake level dropped to a minimum of −8 to −9 m. This level represents the Holocene minimum, and corresponds to the lake terrace observed in the acoustic survey (Fig. 2). A tree stump found at 5.6 m below the modern lake level in the neighbouring Lake Flacher See, dated to 10 693–10 378 cal. a BP, supports a lake-level minimum at that time. At 10 000 cal. a BP, the level of Lake Tiefer See increased again to about −4.5 m by 9000 cal. a BP. Overall, the Early Holocene was a period with high amplitude lake-level fluctuations.

Middle Holocene (9000–4000 cal. a BP). – Middle Holocene sediments are present in only four cores, i.e. peat sections from TS-2, TS-3, TS-17 and gyttja from TS-11. The peat sections indicate a long-term lake-level increase from about −4.5 m at 9000 cal. a BP to about −2.6 m at 4000 cal. a BP. The macrofossil evidence from TS-2, TS-3 and TS-17 points at some fluctuations on top of this trend. Higher lake-levels of about −3 m are indicated at ~7800 to 7600 cal. a BP and ~6500 cal. a BP. Some lake level lowering is indicated at 7000 cal. a BP (to about −4.5 m) and at 6000 cal. a BP (to about −3.5 m).

Late Holocene (4000 cal. a BP to today). – The Late Holocene is well represented in all but three littoral cores from Lake Tiefer See. Peat formation in TS-0 and TS-00 indicates that the lake level increased to at least −1.6 m soon after 4000 cal. a BP. Seeds of the amphibious *Cyperus fuscus* point at pronounced, annual to decadal, lake-level fluctuations at around that time. Peat and gyttja sections e.g. in TS-3 and TS-17 indicate that the lake level has been mostly above −3.1 m after 3000 cal. a BP and mostly above −1.6 m after 2000 cal. a BP. Lacustrine sands in TSK12 and TSK23 (Fig. 3) even suggest maxima above the modern lake level at ~2400 cal. a BP (+0.4 m), ~1800 cal. a BP (+0.2 m), ~600 cal. a BP (+0.6 m) and 270 cal. a BP (+1.0 m). During these periods, the lake level may have occasionally reached the overflow of the lake chain at Lake Bergsee (Fig. 1). The outflow is at a level of +0.7 m (63.7 m NHN) today, and likely was at +2.0 m (65 m

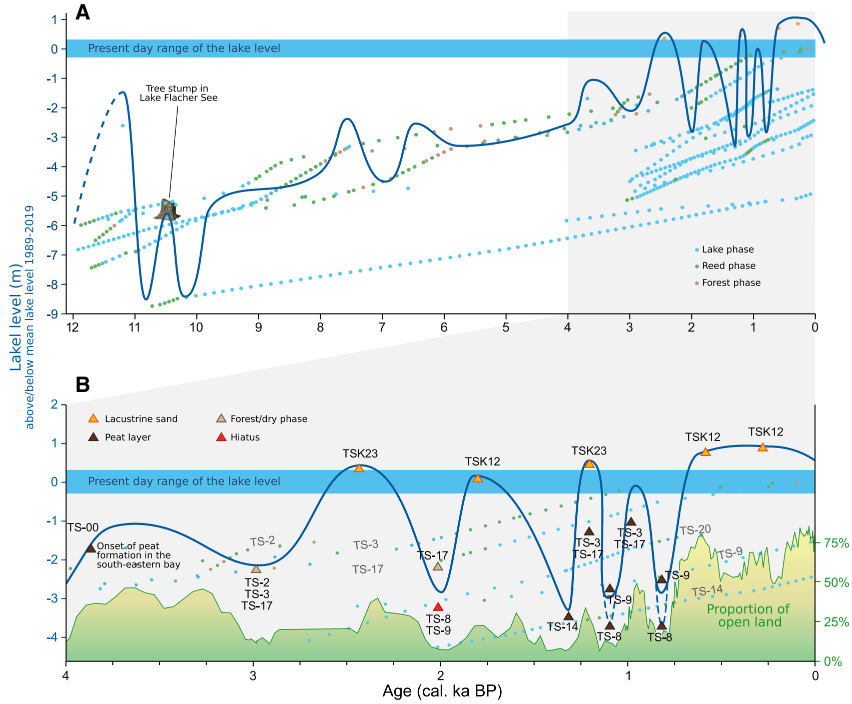

Fig. 3. A. Reconstructed water level of Lake Tiefer See during the Holocene. Dots represent sediment layers from the lake marginal profiles interpreted as lake phase (blue), reed phase (green) and forest phase (brown). B. Lake level reconstruction for the past 4000 years, with key indicator points. Proportion of open vegetation in the surroundings of Lake Tiefer See (green silhouette) was inferred from the DBC pollen record using ROPES.

NHN) in the past. As indicated by peat layers in lake sediments in TS-8, TS-9 and TS-14 (Fig. 3), periods with high lake-levels were interrupted by pronounced minima at ~3000 cal. a BP (−2.0 m), at ~2000 cal. a BP (−1.5 to −2.0 m) and between 1500 and 800 cal. a BP (−2.5 to −3.5 m). All these minima occurred during periods of reduced land use intensity and increased forest cover (Fig. 3).

Periods with a higher lake level during the Late Holocene are also indicated at the neighbouring Lake Flacher See – findings of Bronze Age swords and other objects in the lake indicate a lake level well above −5 m at ~3000 cal. a BP, above −6 m at 2770 cal. a BP and above −2 m at 2550-2600 cal. a BP (Schmidt 2017, 2019, 2020).

EDA analysis

EDA analysis shows major changes in land cover on different soil types during the Holocene in northeastern Germany (Table 4). During the two Early Holocene periods, forest cover was still limited and forests were dominated by birch and pine. From 8000 to 6000 cal. a BP forests cover was high on all soil types (>90%); areas with Cambisols were dominated by *Betula*, *Pinus*, areas with Luvisols by *Corylus*, *Fraxinus*, *Pinus*, *Ulmus*, areas with Gley-/Stagnosols by *Alnus*, *Corylus*, *Fraxinus*, *Tilia*, *Ulmus* and areas with Histosols by *Alnus*, *Fraxinus*. From 4000–3000 cal. a BP (Bronze Age period) the cover of open taxa increased to 30–45% on all soil types. Intense land use in the area is confirmed by rich archaeological evidence from the neighbouring Lake Flacher See (Schmidt 2017, 2019, 2020). From 1350–1550 cal. a BP (Migration Period), forest cover was again higher, i.e. ~90% on Cambisols and 50–70% on the other soil types (Table 4). Forests of that period were dominated by *Fagus* and *Carpinus*. From 750–650 cal. a BP (Medieval Period) open vegetation prevailed on all soil types; forest cover was reduced to between ~10% on Gley-/Stagnosols and ~40% on Histosols. Today, the forests cover of the study region is about 20%, i.e. slightly higher than during the Medieval Period.

We projected the EDA results on the surface catchment of Lake Tiefer See (Table 5). The catchment (~4.6 km²) is dominated by Luvisols (56.3%) and Gley-/Stagnosols (40.4%) while Cambisols are rare (6.3%) and Histosols absent. We estimate a high cover of pine in the Early Holocene, i.e. ~35% by 11 500 cal. a BP and of ~57% by 11 000 cal. a BP. Open vegetation still covers ~28% by 11 500 cal. a BP and ~25% by 11 000 cal. a BP. From 8000–6000 cal. a BP, broad-leaved trees (73%) dominated, pine (17%) and open vegetation were rare (3%). From 4000–3000 cal. a BP (Bronze Age), open vegetation (66%) prevailed and broad-leaved trees (30%) were rarer. From 1550 to 1350 cal. a BP (Migration Period) broad-leaved trees, including beech, were again

Table 4. Results of EDA analysis, given as mean abundance of 19 major plant taxa on the four major soil types of northeastern Germany during four study periods.

	Alnus	*Betula*	*Carpinus*	*Corylus*	*Fagus*	*Fraxinus*	*Picea*	*Pinus*	*Quercus*	*Tilia*	*Ulmus*	*Artemisia*	*Calluna*	Cereals	Cyperaceae	Grasses	*Pla. lan.*	*Rumex*	*Secale*
Medieval Period (750–650 cal. a BP)																			
Cambisols (6.3%)	4.1	4.2	2.3	0.6	7.4	0.5	0.5	5.7	4.5	0.2	0.4	0.5	3.6	11.9	6.3	32.1	1.0	2.0	12.3
Luvisols (56.3%)	1.1	0.6	1.6	0.9	9.5	1.0	0.5	0.5	1.8	0.2	0.6	0.4	1.7	27.2	1.9	31.1	1.2	2.1	16.0
Gley-/Stagnosols (40.4%)	0.6	0.4	1.4	0.7	1.4	1.7	0.6	0.8	1.2	0.3	0.5	0.4	3.0	13.2	16.7	37.2	1.5	2.9	15.3
Histosols (0%)	6.1	5.6	1.4	1.6	1.1	0.7	0.8	20.4	2.3	0.5	0.5	1.3	7.9	1.0	14.7	22.3	3.0	2.9	6.0
Migration Period (1350–1550 cal. a BP)																			
Cambisols (6.3%)	5.8	6.7	12.9	0.3	43.8	2.4	0.5	5.0	9.2	0.6	0.9	0.2	4.0	2.3	1.2	2.8	0.4	0.3	0.4
Luvisols (56.3%)	5.3	0.5	7.8	2.2	30.3	3.0	0.5	0.3	2.1	0.2	0.9	0.3	0.4	18.7	1.6	22.6	1.4	0.7	1.2
Gley-/Stagnosols (40.4%)	6.2	1.0	17.4	2.6	36.7	3.5	0.5	0.4	2.8	0.2	0.8	0.4	1.0	1.7	6.6	10.5	1.6	1.1	5.0
Histosols (0%)	10.9	2.3	3.6	2.0	27.1	4.3	0.7	8.1	1.9	0.7	0.9	0.4	2.4	1.0	5.7	23.3	1.0	0.7	2.9
Bronze Age (4000–3000 cal. a BP)																			
Cambisols (6.3%)	6.1	4.9	1.1	1.6	3.2	1.4	0.5	18.1	9.7	1.6	0.6	0.8	5.8	3.5	7.0	31.4	1.2	1.2	0.2
Luvisols (56.3%)	7.4	1.2	0.5	6.8	1.1	5.9	0.9	0.5	1.8	2.5	2.5	1.3	1.3	4.6	6.1	45.8	6.7	2.7	0.3
Gley-/Stagnosols (40.4%)	4.9	2.7	0.7	8.4	2.0	4.3	1.0	0.7	5.4	2.4	2.8	1.0	6.2	4.2	7.6	43.2	1.3	0.7	0.3
Histosols (0%)	4.7	11.2	2.2	0.7	1.7	1.6	1.7	22.6	1.6	0.8	0.9	0.8	2.2	2.4	6.6	29.7	5.0	3.3	0.3
Middle Holocene forest period (8000–6000 cal. a BP)																			
Cambisols (6.3%)	2.4	10.3	0.2	2.0	0.5	3.8	1.4	44.6	9.6	4.1	5.5	0.5	–	–	–	13.5	–	–	–
Luvisols (56.3%)	0.0	4.7	0.4	28.7	1.3	14.5	0.1	26.7	0.0	0.0	13.1	0.3	–	–	–	0.0	–	–	–
Gley-/Stagnosols (40.4%)	12.7	2.1	0.0	11.7	0.0	16.7	0.0	0.0	8.2	20.1	22.1	0.0	–	–	–	4.5	–	–	–
Histosols (0%)	31.3	0.5	0.3	0.9	0.1	22.8	0.0	0.0	6.8	0.0	7.7	0.0	–	–	–	19.9	–	–	–
Early Holocene PINUS period (~11 000 cal. a BP)																			
Cambisols (6.3%)	0.1	1.4	0.1	0.6	0.1	0.2	0.2	75.1	0.1	0.1	0.5	0.2	0.5	–	4.2	10.7	0.1	0.1	–
Luvisols (56.3%)	0.4	2.8	0.4	3.3	0.4	0.4	0.3	59.3	0.5	0.3	1.6	0.6	1.4	–	4.8	8.7	0.3	0.3	–
Gley-/Stagnosols (40.4%)	0.1	28.8	0.2	1.2	0.2	0.3	0.3	26.2	0.1	0.2	0.6	0.4	0.4	–	5.9	21.2	0.2	0.2	–
Histosols (0%)	0.1	16.6	0.1	0.3	0.2	0.2	0.2	57.9	0.1	0.2	0.4	0.3	0.4	–	2.3	8.7	0.2	0.2	–
Early Holocene BETULA period (~11 500 cal. a BP)																			
Cambisols (6.3%)	0.1	20.8	0.1	0.2	0.2	0.2	0.2	37.2	0.1	0.1	0.2	0.5	0.3	–	8.1	22.9	0.1	0.1	–
Luvisols (56.3%)	0.2	8.8	0.4	0.5	0.5	0.6	0.6	37.1	0.3	0.5	0.6	0.5	0.7	–	10.1	18.2	0.3	0.3	–
Gley-/Stagnosols (40.4%)	0.1	18.7	0.2	0.3	0.3	0.4	0.4	26.6	0.2	0.2	0.4	0.5	0.4	–	9	23.7	0.2	0.3	–
Histosols (0%)	0.1	25.9	0.3	0.2	0.3	0.4	0.4	32	0.2	0.3	0.3	0.3	0.5	–	2.7	20.3	0.2	0.3	–

Table 5. Reconstructed summarized plant abundances in % of total area in the catchment area of Lake Tiefer See during six study periods and today.

Periods	*Pinus*	*Fagus*	Other broad-leaved trees	Arable land	Grassland/open vegetation	Sum
Today	0.8	0.0	2.5	78.7	11.7	93.8
750–650 cal. a BP	1.0	6.1	8.0	36.1	48.3	99.5
1550–1350 cal. a BP	0.7	33.7	28.2	13.4	23.5	99.5
4000–3000 cal. a BP	1.7	1.6	29.8	4.7	61.3	99.1
8000–6000 cal. a BP	17.1	0.7	72.9	0.2	2.7	93.5
~11 000 cal. a BP	57.0	0.0	18.0	0.0	25.0	100.0
~11 500 cal. a BP	35.0	0.0	28.0	0.0	28.0	100.0

dominant (62%) and open vegetation (37%) rarer. Finally, from 750–650 cal. a BP (Medieval Period) open vegetation 84% was again dominant and trees (15%) correspondingly rare. The present cover of open vegetation is ~90%.

Water balance modelling

We estimated potential evaporation with the Hargreaves equation and actual ET from climate data. The resulting fraction ET/P is 74% for forests and 59% for open vegetation. Furthermore, for pine forests in the study region the fraction is 86% (Müller 2011). From that, we calculated ET/P fractions for the reconstructed land cover during six Holocene periods (Table 6).

ET was highest in the Early and Middle Holocene with a high forest cover (>425 mm a^{-1}) and lowest in the open periods of the Late Holocene (<390 mm a^{-1}, Table 6). The estimated groundwater recharge (the difference between P and ET) is hence lower in forest periods and higher in open vegetation periods (Table 6). Recharge is 10–89 mm a^{-1} (= 4–39%) lower than today in all six periods (Table 6). Assuming that the lake level is mainly groundwater controlled, our simple incremental groundwater inflow–outflow calculations suggest that the lower groundwater recharge results in a lake level between 0.6 m lower than today in the Medieval Period and ~6 m lower than today around 11 000 cal. a BP (Table 7). For most periods, the lake-level estimates based on water-balance modelling match the reconstructed lake-levels (R^2 of 0.94 for mean values, Table 7). Only at 11 000 cal. a BP, the reconstructed lake-level (−6.1 to −9.1 m) is about 2 m lower than the lake-level estimate by water balance modelling (−4.2 to −7.7 m), pointing at other, most likely climatic, influences on the lake level.

Discussion

The present lake-level reconstruction of Lake Tiefer See is built on a unique data set of 28 sediment sequences from the lake margin, combined with detailed land cover reconstructions and water balance modelling.

The lake level of Tiefer See was lowest during the Early Holocene followed by a long-term increase to maximum levels between *c.* 1250 and 250 cal. a BP. This general development agrees with previous regional lake-level reconstructions except that for Lake Drewitzer See (Lorenz 2007; Kaiser *et al.* 2012; Fig. 4). Low Early Holocene lake-levels are reported also from western and southern Germany, i.e. Degersee, Steißlinger See and Hämelsee (Kleinmann *et al.* 2000; Kalis *et al.* 2003), from Poland (Gałka *et al.* 2014, 2015; Pleskot *et al.* 2018) and from southern Sweden (Gaillard & Digerfeldt 1991; Digerfeldt *et al.* 2013). In contrast, Magny *et al.* (2011) found high lake-levels during the Early Holocene.

The high temporal resolution of the present lake-level reconstruction furthermore revealed a brief lake-level increase between ~10 800 and 10 500 cal. a BP, interrupting the lowstand, and short-lived lake-level fluctuations in the Late Holocene, which have not been reported from other lakes. We also find evidence for an as-yet unknown lake level maximum in the first centuries of the Holocene.

During the Middle Holocene (9000–4000 cal. a BP) the level of Lake Tiefer See increased from ~–4.5 to −2.5 m. Reconstructions from the lakes Krakower See, Krummer See and Müritz show a similar pattern with a rising lake level from about 9000–7000 cal. a BP, a maximum between 7000 and 6000 cal. a BP and a stable or slightly lower lake level from 6000 to 4000 cal. a BP (Fig. 4). The only exception is a reconstruction for lake

Table 6. Results of water balance modelling: mean annual water budget parameters for each period.

Period	ET/P (mm mm^{-1})	ET act (mm a^{-1})	P-ET = GW recharge (mm a^{-1})	Difference from today's recharge (mm a^{-1})
Today	0.61	361	230	–
750–650 cal. a BP	0.63	371	220	10
1350–1550 cal. a BP	0.70	415	176	55
4000–3000 cal. a BP	0.66	389	202	28
8000–6000 cal. a BP	0.72	425	166	65
~11 000 cal. a BP	0.76	449	142	89
~11 500 cal. a BP	0.72	427	164	66

Table 7. Water levels estimated with the simple water balance model (assuming that the land cover changed but not the climate) compared to lake-levels reconstructed from marginal cores. Minimum, maximum and mean values of the calculated lake-levels are based on a range of different initial conditions, thus accounting for some of the uncertainty in the assumptions. All values given relative to the mean present water level.

Periods	Water level reconstructed from sediment cores (m)			Water level from water balance modelling (m)		
	Min.	Mean	Max.	Min.	Mean	Max.
750–650 cal. a BP	0.4	0.7	0.9	−0.8	−0.6	−0.5
1350–1550 cal. a BP	−4.1	−3.6	−3.1	−4.2	−3.3	−2.4
4000–3000 cal. a BP	−2.6	−2.1	−1.6	−1.8	−1.4	−1.1
8000–6000 cal. a BP	−5.1	−4.1	−3.1	−5.1	−3.9	−2.9
~11 000 cal. a BP	−9.1	−7.6	−6.1	−7.7	−5.8	−4.2
~11 500 cal. a BP	−6.1	−4.1	−2.1	−5.2	−4.0	−2.9

Drewitzer See, which shows a Middle Holocene lake-level decline. At Lake Tiefer See we furthermore observe two brief maxima around 7500 and 6500 cal. a BP, which appear synchronous to wet phases observed in Poland and in western central Europe (Fig. 4). The second maximum is also synchronous to a period with high lake-levels in Lake Fürstenseer See. Indications of further short-lived highstands reported from other studies (Fig. 4) have not been found at Lake Tiefer See.

During the Late Holocene (4000 cal. a BP–today), the level of Lake Tiefer See has mostly been higher than during the Middle Holocene, but has also shown high fluctuations. The highest lake level of ~+1.5 m was found following the Medieval Period, from ~600 to 200 cal. a BP (1350–1750 CE). High Late Holocene lake-levels are a common feature in the region, e.g. in the lakes Drewitzer See, Krakower See, Krummer See, Müritz and Fürstenseer See (Fig. 4). Maxima during and after the Medieval Period have been observed repeatedly (Kaiser *et al.* 2014b; Dietze *et al.* 2016). Increasing lake-levels during the Late Holocene have also been reported from Lake Cerin in the western Alps (Magny *et al.* 2011; Fig. 4). However, the Tiefer See record shows more fluctuations than earlier records, including maxima at ~2500 and ~1800 cal. a BP and minima at ~2000 cal. a BP and between 1200 and 800 cal. a BP.

Note that we are able to identify centennial and shorter lake-level fluctuations in the Late Holocene but mostly

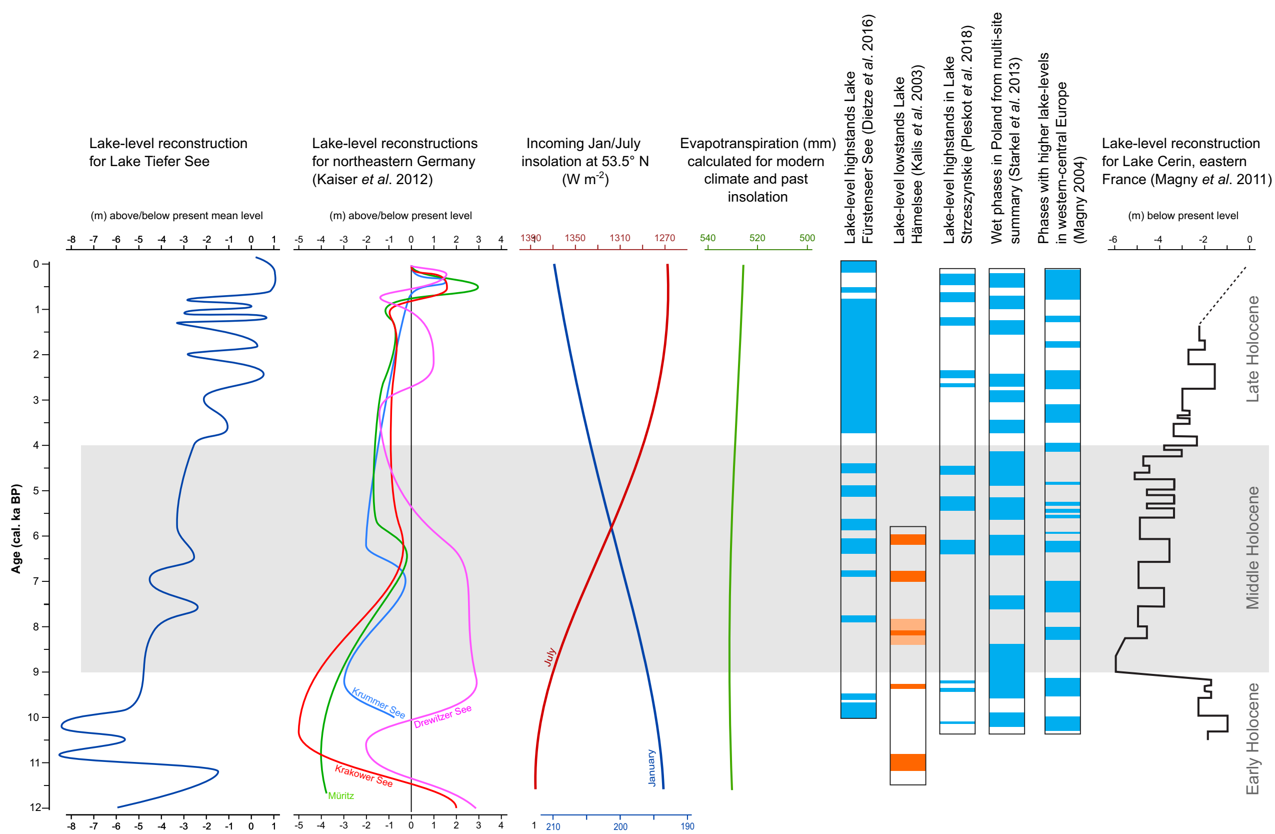

Fig. 4. Comparison of lake-level reconstructions from northeastern Germany and other European studies. Evapotranspiration of a grass reference plot calculated with equation 3 from Oudin et al. (2010) using modern climate but past insolation.

only longer trends in the Early and Middle Holocene because the sedimentary evidence is much richer for the Late Holocene. Due to the high water depth of >60 m, the continuous sediment record from the deepest lake basin is not suited to refining the lake-level reconstruction.

Drivers of Holocene lake-level fluctuations in Lake Tiefer See

Early Holocene (11 600–9000 cal. a BP). – Our reconstruction shows a large amplitude of the lake level (>8 m) during the Early Holocene. It dropped from a near modern level during the first centuries of the Holocene to at least −8 m between 11 000 and 10 000 cal. a BP and increased to −5 m after 10 000 cal. a BP. During that time, vegetation in the study region changed repeatedly. First, the onset of the Holocene triggered the expansion of birch and pine, so that the forest cover increased from ~30% at 11 600 cal. a BP to ~80% by 11 200 cal. a BP (de Klerk *et al.* 2008; Theuerkauf *et al.* 2014). Likely due to further warming, and influenced by other factors such as soil formation and migration, birch and pine were later partly replaced by warm-loving tree taxa, starting with hazel after 10 800 cal. a BP, followed by elm, lime and oak after ~10 000 cal. a BP. The pine cover declined from >50% by ~11 000 cal. a BP to <20% after 10 000 cal. a BP. Water balance modelling suggests that the peak cover of pine from 11 000 to 10 000 cal. a BP corresponds to a minimum in groundwater recharge of 142 mm a^{-1}, 89 mm a^{-1} less than today, because evapotranspiration from pine forests is higher than evapotranspiration from deciduous forests and open vegetation. In our model, this recharge minimum translates into a lake level of −4.2 to −7.7 m, while our reconstruction shows a lake level at −8 to −9 m. The difference likely points at the climatic influence. With pine being partly replaced by deciduous trees after 10 000 cal. a BP, our model indicates an increase in recharge from 142 to 166 mm a^{-1}, resulting in a lake level of −2.9 to −5.1 m. This level is similar to the reconstructed lake level of about −4 m by ~9000 cal. a BP.

Since we do not have evidence to reconstruct the lake level during the Younger Dryas, we are not able to investigate the influence of the major warming at the onset of the Holocene on the lake level. However, we suggest that the largely open vegetation and related high groundwater recharge can explain the high lake level in the first centuries of the Holocene. Since the peak in pine cover between 11 000 and 10 000 cal. a BP coincides with the major lake-level lowering, we infer that Early Holocene land cover changes significantly contributed to the lake-level dynamics.

Early Holocene lake-level lowstands have been observed repeatedly across central Europe and commonly were attributed to dry or warm climatic conditions (Kalis *et al.* 2003; Kaiser *et al.* 2012). Lauterbach *et al.* (2011) explained regionally dry climate in the Baltic region with the remaining Scandinavian ice shield that led to the formation of an anticyclonic circulation and blocking of moist westerlies. Persistent dry climatic conditions during the Early Holocene have also been described for the Balkans (Wright *et al.* 2003; Connor *et al.* 2013). A prominent short-lived decline in tree pollen (mainly PINUS) in eastern central Europe, tentatively dated to 11 200 cal. a BP, may indicate that the dry conditions temporarily expanded into central Europe (Theuerkauf *et al.* 2014). However, there is no consistent evidence for one or several dry periods between 11 000 and 10 000 cal. a BP across central Europe. A dry event may be indicated by a synchronous, low level of Lake Kojle-Perty in northeastern Poland (Gałka *et al.* 2015). Intensified fires just after ~11 200 cal. a BP in southeastern Poland (Kołaczek *et al.* 2017, 2018) may also point at a dry event, yet a composite charcoal record from northeastern Germany shows low burning intensity around 11 000 cal. a BP (Dietze *et al.* 2018). Stančikaitė *et al.* (2015) report higher lake-levels between 11 300 and 10 800 cal. a BP in Lithuania. In western Europe, van der Plicht *et al.* (2004) separate two climatic events; the assumed dry Rammelbeek phase around 11 400 cal. a BP and a wetter period starting at 11 250 cal. a BP. Magny *et al.* (2011) suggest that rather wet conditions prevailed in eastern France until the final decay of the Fennoscandian Ice Sheet at around 9000 cal. a BP.

As another cause of hydrological changes in lakes and river system during the Early Holocene, Błaszkiewicz *et al.* (2015) and Kaiser *et al.* (2012, 2018a) discuss delayed melting of dead-ice blocks. Dead-ice melting during the Early Holocene has also been reported from Lake Hofsee just south of Lake Tiefer See (Homann *et al.* 2002). Due to the connection of the two lakes, late dead-ice melting in Lake Hofsee may have also affected Lake Tiefer See. In summary, the high amplitude of lake-level fluctuations in Lake Tiefer See likely relate to a combination of factors – the direct impact of the changing climate and the more indirect impact of the changing land cover.

Middle Holocene (9000–4000 cal. a BP). – During the Middle Holocene, we observe a lake-level increase from about −4.5 to −2.5 m, with two brief maxima at ~7500 and ~6500 cal. a BP. The forests established during the Early Holocene remained largely stable until 6000 cal. a BP, when Neolithic farmers started transforming forests into open land (Feeser *et al.* 2019). Until 4000 cal. a BP, forest opening affected less than 25% of the landscape in the Lake Tiefer See area (Dräger *et al.* 2017), and hence likely played a minor role for the observed Middle Holocene lake-level increase. Rising Middle Holocene lake-levels have commonly been attributed to changes in solar insolation, particularly to the decline in summer insolation (e.g. Magny *et al.* 2011). Direct effects of changes in insolation on evapotranspiration were probably small (Fig. 4), but they likely triggered changes in atmospheric circulation resulting in cooler and wetter conditions in the northern mid-latitudes and higher lake levels (Davis & Brewer 2011; Routson *et al.* 2019). In our water balance calculations, a lake-level increase of ~2 m corresponds to an increase in recharge of ~30 mm. To produce such an increase in recharge by changes in precipitation alone would require an increase in precipitation of at least 30 mm a^{-1}. Pollen-based climate reconstructions do not show climatic changes of such magnitude for central Europe (Litt *et al.* 2009; Kühl & Moschen 2012; Mauri *et al.* 2015). The two brief highstands in Lake Tiefer See at 7500 and 6500 cal. a BP are synchronous with elevated lake-levels in Germany, Poland and France (Fig. 4) and likely relate to centennial-scale wet periods (e.g. Magny *et al.* 2011; Starkel *et al.* 2013).

Late Holocene (4000 cal. a BP–today). – For the Late Holocene, our reconstruction suggests predominantly higher levels of Lake Tiefer See with repeated fluctuations from −3.5 to +1.5 m, i.e. approaching the natural outflow of the lake chain. The pollen record from Lake Tiefer See shows recurrent changes in forest cover, including six prominent settlement periods (forest cover 10–50%) interrupted by reforestation periods (forest cover >75%, Fig. 3). Moreover, forest composition changed after about 2800 cal. a BP due to regional expansion of beech (*Fagus sylvatica*) and hornbeam (*Carpinus betulus*). We find that all lake-level maxima occurred during settlement periods (4000–3000, ~2500, ~1800, ~1200, ~1000 and 600–200 cal. a BP), while the minima occurred during reforestation periods (~3000, ~2000, ~1250, ~1100 and ~900 cal. a BP), supporting our hypothesis that the land cover changes have influenced the lake level. Water balance modelling suggests that groundwater recharge was ~55 mm a^{-1} higher during open vegetation periods than during forest periods, which translates into a lake-level increase of about 2–3 m from forest to open vegetation periods. Our lake-level reconstruction shows similar changes. We hence infer that the anthropogenic land cover changes at least partly explain the reconstructed lake-level changes.

A second likely driver for the higher lake level during the Late Holocene is the proposed hemispheric shift to a cooler and wetter climate in response to changes in solar insolation (e.g. Routson *et al.* 2019). However, pollen-based climate reconstructions for central Europe show very small changes in temperatures and precipitation only (Litt *et al.* 2009; Kühl & Moschen 2012; Mauri *et al.* 2015). Alpine flood records show more prominent changes, yet are difficult to interpret in terms of annual precipitation (Czymzik *et al.* 2013; Wirth *et al.* 2013).

Besides the long-term climatic changes, pronounced cool-wet conditions likely prevailed during the 2.8 ka event and the Little Ice Age (e.g. van Geel *et al.* 1996; Martin-Puertas *et al.* 2012; Engels *et al.* 2016). At Lake Tiefer See, the 2.8 ka event is likely represented in a first lake-level maximum above modern levels at ~2500 cal. a BP. During the Little Ice Age, the lake level was also very high, although the period with high lake-levels had already started during the Medieval Period ~300–400 years earlier, likely in response to near-complete deforestation of the study region. The lake level had possibly already reached its maximum, defined by the natural overflow of the lake chain at ~65 m NHN, during the Medieval Period. Elevated water levels in lakes and river systems across northeastern Germany and northern Poland since the Medieval Period have also been favoured by the construction of river and stream dams and related water mills (Starkel 2003; Starkel *et al.* 2013; Kaiser *et al.* 2018b; Brykała & Podgórski 2020), with a regional influence on the hydrography since the 13th century AD (Kaiser *et al.* 2012). Historic documents show the presence of a water mill in the 17th century CE downstream of the Klocksin lake chain, near the village of Jabel. With an altitude of ~65 m NHN, i.e. close to the natural threshold, the mill may have had little effect on Lake Tiefer See.

Conclusions

The present lake-level reconstruction from Lake Tiefer See, northeastern Germany, confirms long-term lake-level trends known from the region, yet has also identified hitherto unknown short-term fluctuations (decades to centuries) particularly during the Early and Late Holocene. The lake-level amplitude was highest during the Early Holocene, with the lake level ranging from high, near modern levels to Holocene minima of at least 8 m lower than today. The lake level then steadily increased during the Middle and Late Holocene, with again prominent fluctuations over the past 4000 years.

The long-term increase during the Middle and Late Holocene corresponds to declining Northern Hemisphere summer insolation and proposed higher precipitation. The short-term fluctuations during the Early and Late Holocene are instead synchronous with major changes in land cover. Moreover, the combination of water balance modelling and land cover reconstructions suggests that the magnitude of short-term lake-levels fluctuations can – at least partly – be explained by changes in groundwater recharge that were caused by the changes in land cover.

We hence conclude that the Holocene lake-level fluctuations in Lake Tiefer See have been driven by interactions between changes in climate, namely precipitation, and natural as well as anthropogenic changes in land cover. The influence of land cover is recognizable during both the Early and the Late Holocene, but it probably was strongest during anthropogenic land cover changes. We suggest that a robust interpretation of past lake-level changes requires quantification of land cover changes in the catchment area and cannot be limited to climate change alone.

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Author contributions. – MT, AB and SL designed the research. MT, SL and MS led the coring of lake marginal sediments. MT analysed pollen, MS analysed macrofossils and SL led geochemical analysis of lake marginal cores. AB and ND contributed analysis of the lake central core (s). TB carried out the hydrological modelling, KK, CK and FK analysed soil profiles from the lake terrace, PF prepared the hydroacoustic survey. JPS contributed archaeological findings. MT led preparation of the manuscript, with support of all co-authors.

Data availability statement. – The data that support the findings of this study are available from the corresponding author upon request.

References

Ad-hoc-AG Boden (eds.) 2005: *Bodenkundliche Kartieranleitung: KA5*. 438 pp. E. Schweizerbart'sche Verlagsbuchhandlung (Nägele und Obermiller), Stuttgart.

Affolter, S., Häuselmann, A. D., Fleitmann, D., Häuselmann, P. & Leuenberger, M. 2015: Triple isotope (δD, δ^{17}O, δ^{18}O) study on precipitation, drip water and speleothem fluid inclusions for a Western Central European cave (NW Switzerland). *Quaternary Science Reviews 127*, 73–89.

Aguilar, C. & Polo, M. J. 2011: Generating reference evapotranspiration surfaces from the Hargreaves equation at watershed scale. *Hydrology and Earth System Sciences 15*, 2495–2508.

Beijerinck, W. 1947: *Zadenatlas der Nederlandsche flora, ten behoeve van de botanie, palaeontologie, bodemcoutuur en warenkennis, omvattende, naast de inheemsche flora, onze belangrijkste cultuurgewassen en verschillende adventiefsoorten*. 316 pp. H. Veenman, Wageningen.

Beug, H.-J. 2004: *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. 542 pp. Verlag Dr. Friedrich Pfeil, München.

Blaauw, M. & Christen, J. A. 2019: *rbacon: Age-Depth Modelling using Bayesian Statistics*. https://cran.r-project.org/web/packages/rbacon/index.html.

Blaga, C. I., Reichart, G.-J., Schouten, S., Lotter, A. F., Werne, J. P., Kosten, S., Mazzeo, N., Lacerot, G. & Sinninghe Damsté, J. S. 2010: Branched glycerol dialkyl glycerol tetraethers in lake sediments: can they be used as temperature and pH proxies? *Organic Geochemistry 41*, 1225–1234.

Błaszkiewicz, M., Piotrowski, J. A., Brauer, A., Gierszewski, P., Kordowski, J., Kramkowski, M., Lamparski, P., Lorenz, S., Noryśkiewicz, A. M., Ott, F., Słowiński, M. & Tyszkowski, S. 2015: Climatic and morphological controls on diachronous postglacial lake and river valley evolution in the area of Last Glaciation, northern Poland. *Quaternary Science Reviews 109*, 13–27.

Bosch, J. M. & Hewlett, J. D. 1982: A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology 55*, 3–23.

Bradbury, J. P., Leyden, B., Salgado-Labouriau, M., Lewis, W. M., Schubert, C., Binford, M. W., Frey, D. G., Whitehead, D. R. & Weibezahn, F. H. 1981: Late Quaternary environmental history of Lake Valencia, Venezuela. *Science 214*, 1299–1305.

Brauer, A., Hajdas, I., Blockley, S. P. E., Bronk Ramsey, C., Christl, M., Ivy-Ochs, S., Moseley, G. E., Nowaczyk, N. N., Rasmussen, S. O., Roberts, H. M., Spötl, C., Staff, R. A. & Svensson, A. 2014: The importance of independent chronology in integrating records of past climate change for the 60–8 ka INTIMATE time interval. *Quaternary Science Reviews 106*, 47–66.

Brykała, D. & Podgórski, Z. 2020: Evolution of landscapes influenced by watermills, based on examples from northern Poland. *Landscape and Urban Planning 198*, 103798, https://doi.org/10.1016/j.landurbplan.2020.103798.

Connor, S. E., Ross, S. A., Sobotkova, A., Herries, A. I. R., Mooney, S. D., Longford, C. & Iliev, I. 2013: Environmental conditions in the SE Balkans since the Last Glacial Maximum and their influence on the spread of agriculture into Europe. *Quaternary Science Reviews 68*, 200–215.

Crist, R. E. & Chardon, C. E. 1941: Changing patterns of land use in the Valencia lake basin of Venezuela. *Geographical Review 31*, 430–443.

Czymzik, M., Brauer, A., Dulski, P., Plessen, B., Naumann, R., von Grafenstein, U. & Scheffler, R. 2013: Orbital and solar forcing of shifts in Mid- to Late Holocene flood intensity from varved sediments of pre-alpine Lake Ammersee (southern Germany). *Quaternary Science Reviews 61*, 96–110.

Davis, B. A. S. & Brewer, S. 2011: A unified approach to orbital, solar, and lunar forcing based on the Earth's latitudinal insolation/temperature gradient. *Quaternary Science Reviews 30*, 1861–1874.

Dearing, J. A. 1997: Sedimentary indicators of lake-level changes in the humid temperate zone: a critical review. *Journal of Paleolimnology 18*, 1–14.

Dietze, E., Słowiński, M., Zawiska, I., Veh, G. & Brauer, A. 2016: Multiple drivers of Holocene lake level changes at a lowland lake in northeastern Germany. *Boreas 45*, 828–845.

Dietze, E., Theuerkauf, M., Bloom, K., Brauer, A., Dörfler, W., Feeser, I., Feurdean, A., Gedminienė, L., Giesecke, T., Jahns, S., Karpińska-Kołaczek, M., Kołaczek, P., Lamentowicz, M., Latałowa, M., Marcisz, K., Obremska, M., Pędziszewska, A., Poska, A., Rehfeld, K., Stančikaitė, M., Stivrins, N., Święta-Musznicka, J., Szal, M., Vassiljev, J., Veski, S., Wacnik, A., Weisbrodt, D., Wiethold, J., Vannière, B. & Słowiński, M. 2018: Holocene fire activity during low-natural flammability periods reveals scale-dependent cultural human-fire relationships in Europe. *Quaternary Science Reviews 201*, 44–56.

Digerfeldt, G. 1986: Studies on past lake-level fluctuations. *In* Berglund, B. E. (ed.): *Handbook of Holocene Palaeoecology and Palaeohydrology*, 127–143. John Wiley & Sons, Chichester.

Digerfeldt, G., Björck, S., Hammarlund, D. & Persson, T. 2013: Reconstruction of Holocene lake-level changes in Lake Igelsjön, southern Sweden. *GFF 135*, 162–170.

Dörfler, W. 2011: Pollenanalytische Untersuchungen zur Vegetations- und Siedlungsgeschichte im Einzugsbereich des Rugensees bei Schwerin. *Römisch-Germanische Forschungen 68*, 315–336.

Dräger, N., Theuerkauf, M., Szeroczyńska, K., Wulf, S., Tjallingii, R., Plessen, B., Kienel, U., Brauer, A., Szeroczynska, 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*, 450–464.

Dreßler, M., Selig, U., Dörfler, W., Adler, S., Schubert, H. & Hübener, T. 2006: Environmental changes and the Migration Period in northern Germany as reflected in the sediments of Lake Dudinghausen. *Quaternary Research 66*, 25–37.

Engels, S., Bakker, M., Bohncke, S., Cerli, C., Hoek, W., Jansen, B., Peters, T., Renssen, H., Sachse, D., van Aken, J., van den Bos, V., van

Geel, B., van Oostrom, R., Winkels, T. & Wolma, M. 2016: Centennial-scale lake-level lowstand at Lake Uddelermeer (The Netherlands) indicates changes in moisture source region prior to the 2.8-kyr event. *The Holocene 26*, 1075–1091.

Fægri, K. & Iversen, J. 1989: *Textbook of Pollen Analysis.* 328 pp. John Wiley & Sons, Chichester.

Feeser, I., Dörfler, W., Kneisel, J., Hinz, M. & Dreibrodt, S. 2019: Human impact and population dynamics in the Neolithic and Bronze Age: multi-proxy evidence from north-western Central Europe. *The Holocene 29*, 1596–1606.

Frahm, J. P. & Frey, W. 1992: *Moosflora*. 528 pp. UTB Ulmer, Stuttgart.

Gaillard, M.-J. & Digerfeldt, G. 1991: Palaeohydrological studies and their contribution to palaeoecological and palaeoclimatic reconstructions. *Ecological Bulletins 41*, 275–282.

Gałka, M., Tobolski, K. & Bubak, I. 2015: Late Glacial and Early Holocene lake level fluctuations in NE Poland tracked by macrofossil, pollen and diatom records. *Quaternary International 388*, 23–38.

Gałka, M., Tobolski, K., Zawisza, E. & Goslar, T. 2014: Postglacial history of vegetation, human activity and lake-level changes at Jezioro Linówek in northeast Poland, based on multi-proxy data. *Vegetation History and Archaeobotany 23*, 123–152.

Gan, G., Liu, Y. & Sun, G. 2021: Understanding interactions among climate, water, and vegetation with the Budyko framework. *Earth-Science Reviews 212*, 103451, https://doi.org/10.1016/j.earscirev.2020.103451.

Gärtner, P. 1998: Neue Erkenntnisse zur jungquartären Landschaftsentwicklung in Nordwestbrandenburg. Eine landschaftsgenetische Studie am Ausgang des Rheinsberger Beckens. Mit pollenanalytischen Untersuchungen von Thomas Schoknecht. *Münchener Geographische Abhandlungen A49*, 95–116.

van Geel, B., Buurman, J. & Waterbolk, H. T. 1996: Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP. *Journal of Quaternary Science 11*, 451–460.

von Grafenstein, U., Erlenkeuser, H., Brauer, A., Jouzel, J. & Johnsen, S. J. 1999: A mid-European decadal isotope-climate record from 15,500 to 5000 years B.P. *Science 284*, 1654–1657.

Grosse-Brauckmann, G. 1972: Über pflanzliche Makrofossilien mitteleuropäischer Torfe. I. Gewebereste krautiger Pflanzen und ihre Bestimmung. *Telma 2*, 19–56.

Grosse-Brauckmann, G. & Streitz, B. 1992: Pflanzliche Makrofossilien mitteleuropäischer Torfe. III. Früchte, Samen und einige Gewebe (Fotos von fossilen Pflanzenresten). *Telma 22*, 53–102.

Herking, C. 2002: Der menschliche Einfluß auf die Vegetation im Umkreis des Ahlebecker Sees des Kleinen Faulen Sees, Kreis Uecker-Randow, im Spiegel pollenanalytischer Untesuchungen. *Archäologische Nachrichten Aus Mecklenburg-Vorpommern 9*, 16–25.

Homann, M., Merkt, J. & Müller, H. 2002: Sedimentologische und pollenanalytische Untersuchungen einiger mecklenburgischer Seen - ein West-Ost-Transekt. *Greifswalder Geographische Arbeiten 26*, 35–38.

Humboldt, A. von. 2000: *Reise durch Venezuela: Auswahl aus den amerikanischen Reisetagebüchern* (M. Faak, Ed.). 667 pp. Akademie Verlag, Berlin.

IUSS Working Group WRB (2015) *World Reference Base for Soil Resources 2014, Update 2015. World Soil Resources Report 106*. 203 pp. FAO, Rome.

Jahns, S. 2000: Late-glacial and Holocene woodland dynamics and land-use history of the Lower Oder valley, north-eastern Germany, based on two, AMS ^{14}C-dated, pollen profiles. *Vegetation History and Archaeobotany 9*, 111–123.

Jahns, S. 2007: Palynological investigations into the Late Pleistocene and Holocene history of vegetation and settlement at the Löddigsee, Mecklenburg, Germany. *Vegetation History and Archaeobotany 16*, 157–169.

Jeschke, L. & Lange, E. 1987: Zur Landschafts- und Vegetationsgeschichte im Gebiet der Sternberger See im Nordwesten der DDR. *Flora 179*, 317–334.

Joosten, H. & de Klerk, P. 2002: What's in a name? Some thoughts on pollen classification, identification, and nomenclature in Quaternary palynology. *Review of Palaeobotany and Palynology 122*, 29–45.

Kaiser, K., Keller, N., Brande, A., Dalitz, S., Hensel, N., Heußner, K.-U., Kappler, C., Michas, U., Müller, J., Schwalbe, G., Weiße, R. & Bens, O. 2018b: A large-scale medieval dam-lake cascade in central Europe: water level dynamics of the Havel River, Berlin-Brandenburg region, Germany. *Geoarchaeology 33*, 237–259.

Kaiser, K., Koch, P. J., Mauersberger, R., Stüve, P., Dreibrodt, J. & Bens, O. 2014a: Detection and attribution of lake-level dynamics in north-eastern central Europe in recent decades. *Regional Environmental Change 14*, 1587–1600.

Kaiser, K., Küster, M., Fülling, A., Theuerkauf, M., Dietze, E., Graventein, H., Koch, P. J., Bens, O. & Brauer, A. 2014b: Littoral landforms and pedosedimentary sequences indicating late Holocene lake-level changes in northern central Europe — a case study from northeastern Germany. *Geomorphology 216*, 58–78.

Kaiser, K., Lorenz, S., Germer, S., Juschus, O., Küster, M., Libra, J., Bens, O. & Hüttl, R. F. 2012: Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climatic and human impact–an overview. *E&G Quaternary Science Journal 61*, 103–132.

Kaiser, K., Oldorff, S., Breitbach, C., Kappler, C., Theuerkauf, M., Scharnweber, T., Schult, M., Küster, M., Engelhardt, C., Heinrich, I., Hupfer, M., Schwalbe, G., Kirschey, T. & Bens, O. 2018a: A submerged pine forest from the early Holocene in the Mecklenburg Lake District, northern Germany. *Boreas 47*, 910–925.

Kalis, A. J., Merkt, J. & Wunderlich, J. 2003: Environmental changes during the Holocene climatic optimum in central Europe - human impact and natural causes. *Quaternary Science Reviews 22*, 33–79.

Katz, N. J. & Katz, S. W. 1933: *Atlas der Pflanzenreste im Torf.* 30 pp. Staatsverlag für landwirtschaftliche Literatur, Moscow.

Katz, N. J. & Katz, S. W. 1977: *Atlas Rastitelnich Ostakow w torfach*. 371 pp. Nedra, Moscow.

Katz, N. J., Katz, S. W. & Kipiani, M. G. 1965: *Atlas and Keys of Fruits and Seeds Occuring in the Quaternary Deposits of the USSR*. 365 pp. Nauka, Moscow.

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*, 535–544.

Kleinmann, A., Merkt, J. & Müller, H. 2000: Climatic lake-level changes in German lakes during the Holocene? 5th ELDP Workshop, Pallanza. *Terra Nostra 2000/7*, 55–63.

de Klerk, P. 2002: Changing vegetation patterns in the Endinger Bruch area (Vorpommern, NE Germany) during the Weichselian Lateglacial and Early Holocene. *Review of Palaeobotany and Palynology 119*, 275–309.

de Klerk, P. 2004: Vegetation history and landscape development of the "Friedländer Große Wiese" region (Vorpommern, NE Germany) inferred from four pollen diagrams of Franz Fukarek. *Eiszeitalter und Gegenwart/Quaternary Science Journal 54*, 71–94.

de Klerk, P. 2005: A pollen diagram from the Ahlbecker Seegrund (Ueckermünder Heide, Vorpommern, NE Germany) from the legacy of Franz Fukarek. *Archiv für Naturschutz und Landschaftsforschung 44*, 93–108.

de Klerk, P. 2007: A pollen diagram of the Moorer Busch near Grevesmühlen (NW Mecklenburg, NE Germany) from the legacy of Franz Fukarek. *Archiv für Naturschutz und Landschaftsforschung 46*, 3–16.

de Klerk, P. 2008: Patterns in vegetation and sedimentation during the Weichselian Late-glacial in north-eastern Germany. *Journal of Biogeography 35*, 1308–1322.

Kołaczek, P., Margielewski, W., Gałka, M., Apolinarska, K., Płóciennik, M., Gąsiorowski, M., Buczek, K. & Karpińska-Kołaczek, M. 2017: Five centuries of the Early Holocene forest development and its interactions with palaeoecosystem of small landslide lake in the Beskid Makowski Mountains (Western Carpathians, Poland) — high resolution multi-proxy study. *Review of Palaeobotany and Palynology 244*, 113–127.

Kołaczek, P., Płóciennik, M., Gałka, M., Apolinarska, K., Tosik, K., Gąsiorowski, M., Brooks, S. J. & Karpińska-Kołaczek, M. 2018: Persist or take advantage of global warming: a development of Early Holocene riparian forest and oxbow lake ecosystems in Central Europe. *Quaternary Science Reviews 200*, 191–211.

Körber-Grohne, U. 1964: Bestimmungsschlüssel für subfossile Juncus-Samen und Gramineen-Früchte. *Probleme der Küstenforschung im südlichen Nordseegebiet 7*, 1–47.

Kühl, N. & Moschen, R. 2012: A combined pollen and 18O Sphagnum record of mid-Holocene climate variability from Dürres Maar (Eifel, Germany). *The Holocene 22*, 1075–1085.

Lamarche, G. & Lurton, X. 2018: Recommendations for improved and coherent acquisition and processing of backscatter data from seafloor-mapping sonars. *Marine Geophysical Research 39*, 5–22.

Lamentowicz, M., Marcisz, K., Guzowski, P., Gałka, M., Diaconu, A.-C. & Kołaczek, P. 2020: How Joannites' economy eradicated primeval forest and created anthroecosystems in medieval Central Europe. *Scientific Reports 10*, 18775, https://doi.org/10.1038/s41598-020-75692-4.

Lasch, P., Suckow, F., Gutsch, M. & Reyer, C. 2012: Waldumbau in Brandenburg: Grundwasserneubildung unter Klimawandel. *In* Grünewald, U., Bens, O., Fischer, H., Hüttl, R. F., Kaiser, K. & Knierim, A. (eds.): *Wasserbezogene Anpassungsmaßnahmen an den Landschafts- und Klimawandel*, 272–279. Schweizerbart, Stuttgart.

Lauterbach, S., Brauer, A., Andersen, N., Danielopol, D. L., Dulski, P., Hüls, M., Milecka, K., Namiotko, T., Plessen, B., von Grafenstein, U. & Participants, D. 2011: Multi-proxy evidence for early to mid-Holocene environmental and climatic changes in northeastern Poland. *Boreas 40*, 57–72.

Leng, M. J. & Marshall, J. D. 2004: Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews 23*, 811–831.

Litt, T., Schölzel, C., Kühl, N. & Brauer, A. 2009: Vegetation and climate history in the Westeifel Volcanic Field (Germany) during the past 11 000 years based on annually laminated lacustrine maar sediments. *Boreas 38*, 679–690.

Lorenz, S. 2007: *Die spätpleistozäne und Holozäne Gewässernetzentwicklung im Bereich der Pommerschen Haupteisrandlage Mecklenburgs.* Ph.D. thesis, Greifswald University, 351 pp.

Magny, M. 1992: Holocene lake-level fluctuations in Jura and the northern subalpine ranges, France: regional pattern and climatic implications. *Boreas 21*, 319–334.

Magny, M. 2004: Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. *Quaternary International 113*, 65–79.

Magny, M., Bossuet, G., Ruffaldi, P., Leroux, A. & Mouthon, J. 2011: Orbital imprint on Holocene palaeohydrological variations in west-central Europe as reflected by lake-level changes at Cerin (Jura Mountains, eastern France). *Journal of Quaternary Science 26*, 171–177.

Magny, M., Vanniére, B., de Beaulieu, J.-L., Bégeot, C., Heiri, O., Millet, L., Peyron, O. & Walter-Simonnet, A.-V. 2007: Early-Holocene climatic oscillations recorded by lake-level fluctuations in west-central Europe and in central Italy. *Quaternary Science Reviews 26*, 1951–1964.

Martin-Puertas, C., Matthes, K., Brauer, A., Muscheler, R., Hansen, F., Petrick, C., Aldahan, A., Possnert, G. & van Geel, B. 2012: Regional atmospheric circulation shifts induced by a grand solar minimum. *Nature Geoscience 5*, 397–401.

Matjuschenko, W. 1924: Schlüssel zur Bestimmung der in den Mooren vorkommenden Carexarten. *Geologisches Archiv, Zeitschrift für das Gesamtgebiet der Geologie 3*, 183–188, 192–193.

Mauri, A., Davis, B. A. S., Collins, P. M. & Kaplan, J. O. 2015: The climate of Europe during the Holocene: a gridded pollen-based reconstruction and its multi-proxy evaluation. *Quaternary Science Reviews 112*, 109–127.

Michaelis, D. 2001: Ein Schlüssel zur Bestimmung von Braunmoosen in Torfen anhand einzelner Blättchen. *Telma 31*, 79–104.

Moore, P. D., Webb, J. A. & Collinson, M. E. 1991: *Pollen Analysis.* 216 pp. Blackwell Scientific Publications, London.

Mrotzek, A. 2017: 34. Carwitzer See (north-eastern Germany): regional vegetation development during the past 7000 years. *Grana 56*, 318–320.

Müller, H. M. 1962: *Pollenanalytische Untersuchungen im Bereich des Meßtischblattes Thurow/Südostmecklenburg*. Ph.D. thesis, University of Halle, 203 pp.

Müller, J. 2011: Die Anwendung von Lysimetern zur Ermittlung des Wasserhaushaltes in Wäldern des nordostdeutschen Tieflands. *Waldökologie, Landschaftsforschung und Naturschutz 12*, 37–46.

Natkhin, M., Steidl, J., Dietrich, O., Dannowski, R. & Lischeid, G. 2012: Differentiating between climate effects and forest growth dynamics effects on decreasing groundwater recharge in a lowland region in Northeast Germany. *Journal of Hydrology 448–449*, 245–254.

Nilsson, Ö. & Hjelmqist, H. 1967: Studies on the nutlet structure of South Scandinavian species of Carex. *Botaniska Notiser 120*, 460–485.

Oudin, L., Moulin, L., Bendjoudi, H. & Ribstein, P. 2010: Estimating potential evapotranspiration without continuous daily data: possible errors and impact on water balance simulations. *Hydrological Sciences Journal 55*, 209–222.

Peel, M. C., McMahon, T. A. & Finlayson, B. L. 2010: Vegetation impact on mean annual evapotranspiration at a global catchment scale. *Water Resources Research 46*, W09508, https://doi.org/10.1029/2009WR008233.

Pleskot, K., Tjallingii, R., Makohonienko, M., Nowaczyk, N. & Szczuciński, W. 2018: Holocene paleohydrological reconstruction of Lake Strzeszyńskie (western Poland) and its implications for the central European climatic transition zone. *Journal of Paleolimnology 59*, 443–459.

van der Plicht, J., van Geel, B., Bohncke, S. J. P., Bos, J. A. A., Blaauw, M., Speranza, A. O. M., Muscheler, R. & Björck, S. 2004: The Preboreal climate reversal and a subsequent solar-forced climate shift. *Journal of Quaternary Science 19*, 263–269.

Preusser, F., Degering, D., Fuchs, M., Hilgers, A., Kadereit, A., Klasen, N., Krbetschek, M., Richter, D. & Spencer, J. Q. G. 2008: Luminescence dating: basics, methods and applications. *E&G Quaternary Science Journal 57*, 95–149.

Rach, O., Engels, S., Kahmen, A., Brauer, A., Martín-Puertas, C., van Geel, B. & Sachse, D. 2017: Hydrological and ecological changes in western Europe between 3200 and 2000 years BP derived from lipid biomarker δD values in lake Meerfelder Maar sediments. *Quaternary Science Reviews 172*, 44–54.

R Core Team 2020: *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Routson, C. C., McKay, N. P., Kaufman, D. S., Erb, M. P., Goosse, H., Shuman, B. N., Rodysill, J. R. & Ault, T. 2019: Mid-latitude net precipitation decreased with Arctic warming during the Holocene. *Nature 568*, 83–87.

Schlaak, N. & Schoknecht, T. 2002: Geomorphologische und palynologische Untersuchungen im Vorland der Pommerschen Eisrandlage am Beispiel der Bugsinseerinne (Nordbrandenburg). *Greifswalder Geographische Arbeiten 26*, 101–105.

Schmidt, J.-P. 2017: Ein Fremdling im Nordischen Kreis Jungbronzezeitliche Funde aus dem Flachen See bei Sophienhof, Lkr. Mecklenburgische Seenplatte. *Universitätsforschungen zur Prähistorischen Archäologie 297*, 271–281.

Schmidt, J.-P. 2019: Ein bronzenes Hallstattschwert der Periode VI aus dem Flachen See bei Sophienhof, Lkr. Mecklenburgische Seenplatte. *Archäologische Berichte aus Mecklenburg-Vorpommern 26*, 26–34.

Schmidt, J.-P. 2020: "Aller guten Dinge sind drei!" – Ein weiteres bronzezeitliches Schwert aus dem Flachen See bei Lütgendorf, Lkr. Mecklenburgische Seenplatte. *Archäologische Berichte aus Mecklenburg-Vorpommern 27*, 49–55.

Schoch, W. H., Pawlick, B. & Schweingruber, F. H. 1988: *Botanische Makroreste.* 227 pp. Haupt, Bern.

Schoknecht, T. 1996: *Pollenanalytische Untersuchungen zur Vegetations-, Siedlungs- und Landschaftsgeschichte in Mittelmecklenburg - Beiträge zur Ur- und Frühgeschichte Mecklenburg-Vorpommerns, Band 29*. 68 pp. Landesamt für Kultur und Denkmalpflege, Lübstorf.

Schwarz, A. 2006: Rekonstruktion der Entwicklung des Schulzensees und des Tiefen Sees (Mecklenburg-Vorpommern) seit dem Spätglazial mittels Diatomeenanalyse unter besonderer Berücksichtigung der Trophiegeschichte. *Greifswalder Geographische Arbeiten 41*, 1–166.

Stančikaitė, M., Šeirienė, V., Kisielienė, D., Martma, T., Gryguc, G., Zinkutė, R., Mažeika, J. & Šinkūnas, P. 2015: Lateglacial and early Holocene environmental dynamics in northern Lithuania: a multi-proxy record from Ginkūnai Lake. *Quaternary International 357*, 44–57.

Starkel, L. 2003: Palaeohydrology of Central Europe. *In* Gregory, K. J. & Benito, G. (eds.): *Palaeohydrology: Understanding Global Change*, 87–103. John Wiley & Sons, Chichester.

Starkel, L., Michczyńska, D., Krąpiec, M., Margielewski, W., Nalepka, D. & Pazdur, A. 2013: Progress in the Holocene chrono-climatostratigraphy of Polish territory. *Geochronometria 40*, 1–21.

Stockmarr, J. 1971: Tablets with spores used in absolute pollen analysis. *Pollen et Spores 13*, 615–621.

Strahl, J. 2005: Zur Pollenstratigraphie des Weichselspätglazials von Berlin-Brandenburg. *Brandenburger geowissenschaftliche Beiträge 12*, 87–112.

Stuiver, M. 1970: Oxygen and carbon isotope ratios of fresh-water carbonates as climatic indicators. *Journal of Geophysical Research 75*, 5247–5257.

Succow, M. & Joosten, H. 2001: *Landschaftsökologische Moorkunde*. 622 pp. E. Schweitzerbart'sche Verlagsbuchh, Stuttgart.

Sugita, S. 2007: Theory of quantitative reconstruction of vegetation I: pollen from large sites REVEALS regional vegetation composition. *The Holocene 17*, 229–241.

Theuerkauf, M. & Couwenberg, J. 2017: The extended downscaling approach: a new R-tool for pollen-based reconstruction of vegetation patterns. *The Holocene 27*, 1252–1258.

Theuerkauf, M. & Couwenberg, J. 2018: ROPES reveals past land cover and PPEs from single pollen records. *Frontiers in Earth Science 6*, 14, https://doi.org/10.3389/feart.2018.00014.

Theuerkauf, M., Bos, J. A. A., Jahns, S., Janke, W., Kuparinen, A., Stebich, M. & Joosten, H. 2014: *Corylus* expansion and persistent openness in the early Holocene vegetation of northern central Europe. *Quaternary Science Reviews 90*, 183–198.

Theuerkauf, M., Dräger, N., Kienel, U., Kuparinen, A. & Brauer, A. 2015: Effects of changes in land management practices on pollen productivity of open vegetation during the last century derived from varved lake sediments. *The Holocene 25*, 733–744.

Walker, I. R., Mott, R. J. & Smol, J. P. 1991: Allerød—Younger Dryas lake temperatures from midge fossils in Atlantic Canada. *Science 253*, 1010–1012.

Wirth, S. B., Glur, L., Gilli, A. & Anselmetti, F. S. 2013: Holocene flood frequency across the Central Alps – solar forcing and evidence for variations in North Atlantic atmospheric circulation. *Quaternary Science Reviews 80*, 112–128.

Wright, H. E., Ammann, B., Stefanova, I., Atanassova, J., Margalitadze, N., Wick, L. & Blyakharchuk, T. A. 2003: Late-glacial and Early-Holocene dry climates from the Balkan Peninsula to Southern Siberia. *In* Tonkov, S. (ed.): *Aspects of Palynology and Palaeoecology*, 127–136. Pensoft Publishers, Sofia.

Wulf, S., Dräger, N., Ott, F., Serb, J., Appelt, O., Guðmundsdóttir, E., van den Bogaard, C., Słowiński, M., Błaszkiewicz, M. & Brauer, A. 2016: Holocene tephrostratigraphy of varved sediment records from Lakes Tiefer See (NE Germany) and Czechowskie (N Poland). *Quaternary Science Reviews 132*, 1–14.

Zhang, L., Dawes, W. R. & Walker, G. R. 2001: Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources 37*, 701–708.

Supporting Information

Additional Supporting Information to this article is available at http://www.boreas.dk.

Data S1. Summarized description of the sediment cores.

Data S2. Data on soil profiles from the lake terrace.

Fig S1. Map of pollen records used in EDA analysis.

Table S1. Cores from the margin of Lake Tiefer See and the surrounding peatlands (see also Fig. 1). The mean level of the period 1988–2018, measured at the neighbouring Lake Hofsee, is at 63.10 m NHN.