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A submerged pine forest from the early Holocene in the Mecklenburg Lake District, northern Germany

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For the first time, evidence of a submerged pine forest from the early Holocene could be documented in a central European lake. Subaquatic tree stumps were discovered in Lake Giesenschlagsee at a depth of between 2 and 5 m using scuba divers, side-scan sonar and a remotely operated vehicle. Several erect stumps, anchored to the ground by roots, represent an *in situ* record of this former forest. Botanical determination revealed the stumps to be Scots pine (*Pinus sylvestris*) with an individual tree age of about 80 years. The trees could not be dated by means of dendrochronology, as they are older than the regional reference chronology for pine. Radiocarbon ages from the wood range from 10 880±210 to 10 370±130 cal. a BP which is equivalent to the mid-Preboreal to early Boreal biozones. The trees are rooted in sedge peat, which can be dated to this period as well, using pollen stratigraphic analysis. Tilting of the peat bed by 4 m indicates subsidence of the ground due to local dead ice melting, causing the trees to become submerged and preserved for millennia. Together with recently detected Lateglacial *in situ* tree occurrences in nearby lakes, the submerged pine

forest at Giesenschlagsee represents a new and highly promising type of geo-bio-archive for the wider region. Comparable *in situ* pine remnants occur at some terrestrial (buried setting) and marine sites (submerged setting) in northern central Europe and beyond yet partly differ in age. In general, the *in situ* pine finds document shifts of the zonal boreal forest ecosystem during the late Quaternary.

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Subfossil trees and their depositional settings play a considerable role in palaeoclimatic and palaeoenvironmental reconstructions. On the one hand, wood samples are subjected to dendrochronological and isotopic analyses which, for instance, yield temperature, moisture and fire records of the past (e.g. Grudd *et al.* 2008). On the other hand, the depositional environment in which the tree is embedded indicates local site conditions as well as sedimentation and geomorphic processes prior, during and after tree life. Different depositional environments worldwide offer opportunities to examine occurrences of subfossil trees to the full. Examples of such environments bearing trees are seas (Fujii *et al.* 1986), rivers (Kumaran *et al.* 2014), lakes (Hunter *et al.* 2006), mires (Edvardsson *et al.* 2014), mountain lakes and glaciers (Millar *et al.* 2006; Joerin *et al.* 2008), and dunes (Friedrich *et al.* 2001).

Subfossil trees found *in situ* are of particular interest as they offer an opportunity to reconstruct the local environment and thus life-history of tree stands in detail. But ubiquitous erosion and decomposition processes during the Quaternary reduce the chances of discovering trees in their original locations. The rare localities that do offer such records are connected to potentially fast depositing environments, such as river floodplains, alluvial fans, tephra deposits, bogs or dunes (Pregitzer *et al.* 2000; Noshiro *et al.* 2002; Edvardsson *et al.* 2016; Murton *et al.* 2017), as well as to former land surfaces in shallow waters which were rapidly submerged following both marine and lacustrine water level increases (Langridge *et al.* 2012; Gontz *et al.* 2013).

Over the last two decades, several subfossil *in situ* trees were found in the formerly glaciated landscapes of northern central Europe, which were partly deglaciated as recently as the late Weichselian (*c.* 24-15 cal. ka BP; Hughes *et al.* 2016). The recently discovered terrestrial and marine sites mainly contain Lateglacial and early Holocene trees (e.g. Friedrich *et al.* 2004; Westphal *et al.* 2011; Dzieduszyńska *et al.* 2014). Further to the north and west considerable research was performed during the last decades on subfossil wood, which was retrieved from lakes in Scandinavia and Scotland, respectively (e.g. Gunnarson 2008; Helama *et al.* 2008; Wilson *et al.* 2012).

Stimulated by the discovery of young (19th/20th century AD) subaquatic *in situ* trees in the Mecklenburg Lake District (Kaiser *et al.* 2015), further systematic diving explorations were conducted in the region in 2014, revealing early Holocene tree remains at Lake Giesenschlagsee and later Lateglacial occurrences in two nearby lakes (Fig. 1A). According to our knowledge, these are the oldest records of subfossil *in situ* trees from lakes in northern central Europe thus far. They represent a newly discovered inland 'geo-bio-archive' in that region, complementing marine findings from the adjacent Baltic Sea (Uścinowicz 2014) and the North Sea (Bicket *et al.* 2016).

The general objective of the present study is to explore the 'submerged forest' at Lake Giesenschlagsee. For the first time, an assemblage of millennia-old trees preserved in their growth positions could be documented in a regional lake, potentially heralding further, as yet to be discovered tree occurrences in the lake-rich glacial landscapes of central Europe. Therefore, this study aims (i) to identify subaquatic trees and thereby evaluate the potential of different prospection methods, (ii) describe the dendrological properties and undertake radiometric dating of the trees, and (iii) connect the trees to the lake sediment stratigraphy and lake basin development including site conditions during tree growth. Furthermore, the study investigates how the wood could have been preserved (taphonomy) and which comparable records exist in northern central Europe and beyond.

Study site

The study site is situated in the Mecklenburg Lake District, ~90 km northwest of Berlin (Fig. 1A, B). The landscape is part of the lowlands of north-eastern Germany, which were shaped by the Scandinavian inland ice during the Weichselian glaciation up to the Berlin area. Lake Giesenschlagsee (GSS) is located in an outwash plain, a few kilometres south of a terminal zone of the receding late Weichselian inland ice ('Fürstenberger Endmoräne'; Lippstreu *et al.* 1997). GSS is part of a prominent, over 30 km long tunnel valley that extends from north to south and represents a former subglacial channel. The lake is surrounded by sandy glaciofluvial sediments. GSS consists of three basins with a total lake area of 32 ha and a maximum water depth of 23 m in the middle basin (IaG 1995; Fig. 1A, B). Subfossil tree remains, however, have only been found in the northern lake basin thus far (Fig. 1C). This

~15 ha-large basin stretches from the northwest to the southeast, is ~750 m long and 200 m wide with a maximum depth of ~16 m. Several lacustrine landforms shape the shoreline of GSS, such as terraces, fossil cliffs and mire plains. The shoreline of the northern lake basin of GSS is marked by lake terraces constituting an almost circumferential lower level (~ 1 m above the present lake level, max. 40 m in width), and a locally occurring elevated level (~3 m above the present lake level, max. 15 m in width; Fig. 1C). At the western shore, inactive cliff sections rise up from the terraces. The relief surrounding the lake is undulating (mean water level at 58.7 m a.s.l.), rising to a maximal height of 81 m a.s.l.

In the past, GSS was a closed lake basin fed by groundwater from the upper unconfined aquifer and by precipitation onto the lake surface. Today, the lake also has an artificial inlet that brings surface water and an outlet that regulates the lake level. The lake level has fluctuated by only 50 cm within the period of 1972-2014 (Fig. S1). Historic maps suggest that the lake level was ~0.5 to 1 m higher between 1788 and 1888 (Breitbach 2016). GSS has a mesotrophic status and a lower boundary of submerse macrophytes of 5.3 m (Kabus *et al.* 2011). Both influence the degree to which ground structures can be recognised (e.g. potential clear water conditions *vs.* masking of objects).

For the reference period of 1958-1992, the mean annual temperature of the study area was 7.9 °C and the mean annual precipitation was 582 mm (Casper & Koschel 1995).

Today, the catchment of GSS is mainly covered by Scots pine (*Pinus sylvestris*) plantations which replace former deciduous forests dominantly consisting of oak (*Quercus petraea*, *Q. robur*) and beech (*Fagus sylvatica*). During the last centuries, intensive land management, drainage measures and water milling have significantly changed the land cover and hydrography (Krausch 1971).

Material and methods

Prospection and sampling

Between 2014 and 2016, scuba divers recorded and sampled tree remains at GSS which comprised stumps and trunks located at a water depth of between 2 to 5 m (Fig. 2B, C, Table S1). The entire littoral zone in the northern lake basin (Fig. 1C) was surveyed by means of parallel positioned diving tracks up to a depth of ~8 m. A depth finder and hand-held GPS device were used to locate the exact positions of the tree remains. All objects, including profiles (sedimentary sections) below and above the lake level (see below), were referenced to m a.s.l. Wood samples were taken by the divers with a handsaw, cutting entire stem discs or parts thereof.

Local and regional obstacles to finding subaquatic objects are often posed by low visibility due to high lake bio-productivity (trophic state), vegetated lake bottoms and muddy ground. Thus, further subaquatic prospection techniques were applied to assess their potential for studying tree remains in these specific conditions. We used a side-scan sonar to detect subaquatic tree remains in the northernmost part of the lake (~150 x 50 m). Generally, this survey method to detect subaquatic tree remains in lakes has only recently been used (Wilson & Bates 2012). Side-scan sonar produces a detailed sonar picture of the lake bottom, even showing erect objects protruding from the ground. A boat was fitted with a Humminbird 455 kHz bathymetric sonar with precision GPS. Ten survey lines were tracked at ~10 m line spacing, scanning up to a minimal water depth of 2 m. Furthermore, a Remotely Operated Vehicle (ROV) was utilised to provide video sequences and photographs of lake bottom structures (Fig. 2H, I). The VideoRay Pro 4 Standard BASE ROV system deployed is a small (37.5 x 28.9 x 22.3 cm), lightweight (6.1 kg submerse), and cable-controlled device which is operated by one person.

A total of six lake sediment cores (water depths: 0.7-6.7 m; cores GSSB1, GSSB2, GSSB4, GSSB3A, GSSB3B and GSSB5) were retrieved by a percussion corer operated from a raft (Fig. 1C) to undertake a sedimentological analysis of the lake bottom adjacent to the detected tree remains. Furthermore, 24 profiles (21 auger explorations; 3 soil pits, GSSB12, GSSB17a, GSSB17b) were recorded along transects at the north-eastern shoreline of GSS (Fig. 1C), providing information on the stratigraphy of supra-aquatic lake terraces.

Sedimentology

Two profiles (lake sediment core GSSB5, soil pit GSSB12) and a total of 16 samples were subjected to sedimentological laboratory analyses on the matrix matter <2 mm in order to help determine sedimentary facies (Table S2). For grain size analysis, samples were air dried and hand-crushed. If present, organic matter and carbonate were removed using 30% H_2O_2 and 10% HCl, respectively. Grain-size distribution was estimated by wet-sieving. The content of organic matter was estimated by combustion at 550 °C (loss-on-ignition, LOI). $CaCO_3$ was estimated as total inorganic carbon (TIC). It is calculated as total carbon minus total organic carbon (TOC), which was measured by elemental carbon analysis (vario EL elemental analyzer). The classification of soil horizons follows Ad-hoc-AG Boden (2005).

Palaeobotany and dendrochronology

A total of 12 stumps and trunks were detected thus far (Table S1). However, due to heritage conservation considerations only a portion of this total was analysed, comprising seven wood samples for species identification and two samples for dendrochronological analysis.

Wood analysis was conducted by using the identification key for central European tree species (Schoch *et al.* 2004). To that end, the seven samples (Table S1) were analysed in microsections along the transverse, longitudinal-radial and longitudinal-tangential plane under a stereomicroscope (magnification 50-500x).

Pollen analysis was performed on the basal section of lake sediment core GSSB5. Preparation of the seven pollen samples (1 ml volume; *cf.* Fægri & Iversen 1989) included adding one *Lycopodium* tablet (Lund University, batch-Nr. 938934, N~10679 *Lycopodium* spores), treatment with 10% HCl, 20% KOH, sieving (120 µm), and acetolysis (7 min).

Samples were mounted in glycerine. Counting was carried out at 400x magnification. We strove for a minimum count of 300 pollen sum grains per sample. Pollen identification and nomenclature mainly follow Moore *et al.* (1991).

Two tree samples (GSSC3 and Trunk2; Table S1) were subjected to dendrochronological analysis to yield basic tree-ring parameters such as average annual growth rates, tree age and wood density (Speer 2012). For this purpose the wet surfaces of the two discs were cut with a razor blade and the tree ring width measured along two paths per sample using a specific measuring device (LINTAB, F. Rinn SA, Heidelberg, Germany). Wedges were cut from the stem discs, dried and glued to wooden mounts for radiodensitometric analysis. With a twin bladed saw (Walesch Dendrocut) two wooden laths of 1.2 mm thickness were cut and subsequently X-rayed in an ITRAX-multiscanner (Cox analytics, Sweden) operated at 30 kV and 50 mA with an exposure time of 25 ms and an optical resolution of 20 µm. The subsequent radiographic image was analysed with WINDENDRO software and the greyscale was calibrated to radiographic wood densities with the help of a calibration wedge of known material density, which is the standard procedure in wood densitometry.

Radiocarbon dating

Six wood samples from GSS were subjected to radiocarbon (^{14}C) dating at the Poznań radiocarbon laboratory using accelerator mass spectroscopy. Additionally, two samples from occurrences of subfossil wood from the bottom of nearby Lake Wittwesee and Lake Nehmitzsee were dated. The radiocarbon ages from the studied lakes were calibrated with OxCal software version 4.2 (Bronk Ramsey 2009) using the IntCal 13 calibration curve (Reimer *et al.* 2013) and range of 2σ standard deviation for analysis (Table 1). For calibration and graphical display of data on further *in situ* pine occurrences in northern central Europe and beyond the CalPal 2016.3 software (http://www.calpal-online.de/) was used.

Results

Detection and properties of tree remains

Among the three prospection methods, scuba diving was the most reliable in detecting, documenting and sampling subaquatic tree remains (Fig. 2B, C). With side-scan sonar, however, only about 50% of trees known to divers were detectable, partly because this method cannot detect trees in shallow water as it requires a water depth of at least 2 m. Finally, the ROV was useful in searching for trees only in the rare and unpredictable instances of higher water transparency (Fig. 1H, I). The ROV was helpful for documenting (measuring size, taking photographs/videos) and sampling trees detected by the divers. Remote sensing by means of aerial photography, as another potential prospection method, did not help detect subaquatic trees due to the specific conditions of GSS, with trees in greater depth, low water transparency and shading of the shoreline by reed and trees.

In total, 12 subaquatic tree remains were recorded in GSS at a depth of between 2.0 to 5.2 m (Fig. 1, 2, Table S1). Ten trees were found as erect stumps, anchored to the sandy or muddy/peaty ground by roots. Hence, they can be considered *in situ* (life) position records. The term *in situ* is understood here, and analogously in the whole article, as a tree preservation status with intact stem remain (i.e. stump), root and substrate nexus (*cf.* Chapman 1994), disregarding a slightly vertical translocation by local subsidence (see section 'Past tree growth and lake basin development'). The diameter of the stumps ranged from 8 to 50 cm and the height above the current lake bottom varied from 7 to 45 cm. Furthermore, two trunks were recorded. They are 150 and 350 cm long, and 13 and 30 cm wide, respectively. Additionally, small tree remains of up to just a few centimetres were retrieved from a lake sediment core (GSSB5) and a soil pit (GSSB12).

All tree remains had lost their bark. The wood was coated in living filamentous green algae and molluscs (zebra mussel, *Dreissena polymorpha*; Fig. 2E, F). Small cavity-like feeding traces became apparent when this coating was removed (Fig. 2G). The wood inside was firm and could be easily cut using a saw. The fresh cut had a yellowish brown to reddish brown (Fig. 2C, D) colour which, at first glance, implied that the wood could be rather young.

Of the seven wood samples determined from GSS, five were identified as pine (*Pinus* spec.), while the remaining two could only be identified as conifer wood (Table S1). Because Scots pine was besides juniper (*Juniperus communis*) probably the only coniferous tree taxon present in the region in the early Holocene (Lang 1994; Endtmann 2007), also these samples possibly represent Scots pine. As they have a similar macroscopic appearance, the remaining botanically as yet unidentified tree remains may belong to this tree species as well.

Owing to the excellent wood preservation of the two wood samples GSSC3 (early Holocene; see section 'Radiocarbon dating') and Trunk2 (late Holocene), ring measurements and sample preparation for radiodensitometric analyses were straightforward. The samples showed 75 and 92 rings, respectively (Fig. 3D). An additional count for wood sample GSSC6 indicated 65 rings. Average ring width (RW) for GSSC3 was twice as great as for Trunk2 (1.91 mm *vs.* 0.93 mm). Shrinkage of the wood was very low compared to RW measurements of water saturated with air dried wood samples, with only 0.03 mm difference in average RW.

Ring patterns of both trees do not exhibit the typical age-related declining growth trend of a negative exponential shape, which would be typical for open canopy trees (Fritts 2001). Instead, Trunk2 shows an increasing growth trend up to the age of *c.* 45 years and a subsequent growth decline thereafter, whereas GSSC3 shows a declining RW trajectory for the first *c.* 35 years, yet later increases its RW growth, though interrupted by pronounced signature years with low RW (Fig. 3A). Mean sensitivity as a measure of the strength of year to year changes in RW is similar for both samples (GSSC3: 0.22, Trunk2: 0.20) and, compared to modern pine samples, rather low. The very low degree of wood decomposition is also visible in mean wood densities of 0.46 and 0.48 g cm^{-3} for GSSC3 and Trunk2, respectively (Fig. 3B). The values are well within the range for present-day pine wood.

Curves of maximum latewood density (MXD), a parameter frequently used in dendroclimatological reconstructions as a proxy for thermal summer conditions (e.g. Battipaglia *et al.* 2010), exhibit pronounced long-term and inter-annual trends (Fig. 3C). This is probably not caused by wood degradation but instead mirrors climatic or environmental conditions varying during the time of ring formation.

The lack of adequate regional reference chronologies for pine for the time before *c.* 2000 cal. a BP (Friedrich *et al.* 2004) impedes dendrochronological dating of the material at hand.

Sedimentology

The three lake sediment cores GSSB4, GSSB3B and GSSB5 are located along a slope, ranging from 295 to 666 cm water depth (Fig. 4). All cores include about 100 cm of peat and lake sediments, which are partly layered (Fig. 4A, B, Table S2).

The basal sediment in all cores is lacustrine sand (mainly medium sand) with some gravel (LOI: 0-1%, TOC: 0-1%, TIC: 0%). We assume that this sand layer is the true base of the lake sediments, as is even the case in neighbouring lakes for which stratigraphic information exists (Strahl 2005).

The cores include one or two peat layers (LOI: 44-89%, TOC: 11-50%), either directly on top of the sandy base or above a thin basal gyttja layer. The peat is rich in woody remnants, predominantly consisting of pine wood. Pine bark and cones occur, too. The peat matrix is largely made up of sedge radicels. Parts of the peat contain carbonate (TIC: 3-21%).

The upper part includes olive to brownish organic gyttja (LOI: 10-89%, TOC: 4-47%) with low to moderate carbonate content (TIC: 1-15%) and some mollusc remains. Occasionally, charcoal was detected both in the gyttja and the peat, sometimes with large particle sizes of up to 5 mm and higher quantities particularly in the peat.

As early as 2009, coring in the shallow water (2.3 m) of the middle basin of GSS revealed a calcareous gyttja layer covering a rather thick (>40 cm) basal peat layer (S. Lorenz, pers. comm. 2015). This finding appears to mirror evidence gained from stratigraphic analyses of the northern basin lake bottom. Thus, the basal peat layer covered by gyttja seems to be a widespread sedimentary property of GSS.

The lake terraces of GSS were subjected to 21 auger corings and three soil pits (Fig. 1C) to learn more about them in relation to the lake basin stratigraphy and the water level history. Soil pits GSSB17a and GSSB17b reveal a succession of colluvial sand, buried palaeosol (Gleysol and Cambisol, respectively) and basal glaciofluvial sand, whereas soil pit GSSB12, which is located at the lower terrace, exhibits a top layer of lacustrine sand covering peat and gyttja (Figs. 1C, 4C). The surface of this profile is 0.6 m above the recent lake level, corresponding to the height difference between the lake level reconstructed for the 18th/19th century AD and that of today (Breitbach 2016). The lacustrine sand contains dispersed gravel and cobble (max. 11 cm of axis length), and some charcoal, which originates from the erosion of nearby slope sections. There is a rather thin organic horizon (IIGo+fHr) between lacustrine sand and peat layers which is identified as a mixture of eroded peat and lacustrine sand. Several pine wood remains occur in this layer. The subsequent weakly decomposed peat horizon mainly consists of brown moss and radicel remains. A thin layer of coarse organic gyttja with numerous wood remains is followed by an additional moderately to strongly decomposed peat layer predominantly consisting of radicels. It covers minerogenic gyttja.

Palynology

The pollen diagram in lake sediment core GSSB5 covers the section 715 to 745 cm, i.e. the transition from the basal peat layer to the top layer of organic gyttja (Fig. 5). The three lowest samples in the peat layer are dominated by *Pinus* (pine) and *Betula* (birch) pollen, whereas *Corylus* (hazel), *Salix* (willow) and *Ulmus* (elm) pollen are rare. Above the peat layer, *Corylus* pollen percentages increase to about 30%, indicating that the peat layer possibly formed shortly before the early Holocene expansion of hazel in the region between 10 800 and 10 500 cal. a BP (Theuerkauf *et al.* 2014). In the uppermost sample, pollen from thermophilous tree taxa *Quercus* (oak), *Tilia* (lime) and *Alnus* (alder) is well present. Earlier studies suggest that these taxa expanded one after another, i.e. first *Quercus*, then *Tilia* and finally *Alnus*. Therefore, their synchronous appearance in GSSB5 could point to a hiatus but may also result from a sample resolution unsuitably small for a reliable finding at that point.

Furthermore, pollen samples in the peat layer are characterised by high percentages of *Salix* and Wild grass group pollen, while there are only traces of other herb pollen types. High Wild grass group percentages may indicate either a still overall higher openness or presence of grasses, e.g. *Phragmites australis* (reed), near the coring site. The various herb pollen point to the presence of herb-rich, open vegetation, with some *Salix* shrubs. The presence of *Nymphaea* pollen indicates that the site was regularly flooded. High concentrations of both *Sparganium* pollen types at 730 cm suggest reed vegetation, possibly in shallow water.

Radiocarbon dating

Six radiocarbon dates are available from GSS. They comprise dates from subaquatic tree remains of pine or conifer, with four ages clustering in the maximum time span 11 090 to 10 240 cal. a BP, i.e. covering a potential growth period of 850 years (Fig. 6, Table 1). Biostratigraphically this is equivalent to the mid-Preboreal to early Boreal period. Two dates have the same age (GSSC5A/conifer stump: 10 790±270 cal. a BP; GSSB5/pine remains in peat: 10 740±310 cal. a BP). Two further pine stumps probably represent an older (GSSC3: 10 880±210 cal. a BP) and a younger (GSSC6: 10 370±130 cal. a BP) tree age cohort.

Two distinctly younger ages are available from a subaquatic pine tree trunk (Trunk2: 4060±90 cal. a BP) and from a pine remain buried in a lake terrace (GSSB12: 160±160 cal. a

BP), which are equivalent to the mid-Subboreal and late Subatlantic biozones, respectively (Table 1).

Additionally, subaquatic *in situ* pine remains were dated from nearby Lake Nehmitzsee (NES1: 12 670±80 cal. a BP) and Lake Wittwesee (WIS4: 13 530±170 cal. a BP; Fig. 1A, Table 1), yielding Lateglacial ages from the Allerød-Younger Dryas-transition and Bølling to Older Dryas period, respectively.

Discussion

Past tree growth and lake basin development

Extensive subaquatic prospection at GSS revealed several subfossil pine tree stumps and small-scale pine remains (wood, cone, bark) from the early Holocene. A trunk from the late Holocene and smaller wood remains from the recent past were found, too (Fig. 7). The early Holocene tree stumps, including the ground they are rooted in, are remnants of a local tree stand. Nearly 80 year old trees and stem diameters of some 50 cm indicate that a full grown forest existed at this now inundated site. So far only tree stumps from the early Holocene were detected. However, tree trunks may also exist, potentially hidden between basal peat and the covering gyttja (Fig. 7). Radiocarbon dating suggests that trees potentially existed at the site over a period of *c.* 850 years (11 090 to 10 240 cal. a BP). Pollen data indicate that the peat layer in which the stumps are rooted formed before the expansion of hazel in the region, i.e. before between 10 800 and 10 500 cal. a BP (Theuerkauf *et al.* 2014). The age of tree GSSC6 is somewhat younger (10 500-10 240 cal. a BP), which may suggest that the peat layer and former forest soil is not fully preserved. The top part may have been eroded through an increase in the lake level at a later date. We cannot exclude, alternatively, the possibility that the younger date of GSSC6 is related to a post-mortal carbon contamination due to metabolic products of algae, fungi or microbes.

Neither tree growth nor the formation of sedge-dominated peat would have been possible at a submerged site (e.g. Cameron *et al.* 1989; Niinemets & Valladares 2006). Instead, the presence of *in situ* tree remains and the peaty ground suggest that either the former forest soil subsided or that the lake level rose after its formation. The height difference between the uppermost and the lowermost recorded position of the pine stumps and basal peat layers is ~3 m and ~4 m, respectively. Thus, in both cases a significant inclination of the terrain becomes apparent (Fig. 7). The tilting of the sedge peat bed by 4 m is an exceptional sedimentary feature if one assumes an originally synchronous and semi-horizontal peat layer growing in a groundwater dominated setting. By contrast, the late Holocene wood of sample Trunk2, representing a pine trunk lying on the lake bottom in a water depth of 2.5 m, can be explained best by drop from the nearby forested slope (e.g. Wilson & Bates 2012).

Subsidence of the former forest soil could be related to local dead ice melting (Fig. S2). This process is considered responsible for the formation of numerous lake basins in the Weichselian glacial belt of northern central Europe and beyond (e.g. Böse 1995; Niewiarowski 2003; Bennett & Glasser 2009; Kaiser *et al.* 2012a; Błaszkiewicz *et al.* 2015). A considerably long time period comprising thousands of years passed between the decay of the inland ice (in this part of northern Germany between 26-20 ka; Hardt & Böse 2016; Hardt 2017) and the formation of dead ice lakes. While the majority of the basins formed during the Lateglacial (mostly Allerød, i.e. 13.9-12.9 ka), lake formation in several instances was delayed until the early Holocene (i.e. 11.6-9.2 ka; Kaiser *et al.* 2012a; Błaszkiewicz *et al.* 2015). The final phase of dead ice melting was dated to the Preboreal for northern central Europe (Kaiser *et al.* 2007; Słowinski *et al.* 2015) and to the Atlantic for northeastern Europe (Stivrins *et al.* 2017). Alternatively, local subsidence may have been triggered by karst processes in Paleozoic (salt) or Mesozoic (carbonate, gypsum) sediments in the Pre-Pleistocene underground. However, such cases are extremely rare in the wider region, and given the absence of such geological structures these processes are very unlikely to have occurred in the study area (Lippstreu *et al.* 1997).

In lakes in the vicinity of GSS, basin formation has been palynologically and tephrachronologically dated to the Allerød to Preboreal period (Krey & Kloss 1990; Hackelbörger 1995; Homann *et al.* 2002; Brande 2003; Strahl 2005; Schwarz 2006; Küster *et al.* 2012; Fig. 1A). Two of the eight records (GSS, Krummer See) show a late onset of lacustrine sedimentation in the Preboreal, i.e. possibly late basin formation. These observations support the assumption that subsidence might have caused the present subaquatic position of the forest remains at GSS.

By contrast, the sedimentary properties observed at GSS and the permafrost dynamics reconstructed for the last termination in northern Europe (Renssen & Vandenberghe 2003) present evidence against possible alternative explanations, such as an absolute (e.g. climate-driven) lake level rise (see Kaiser *et al.* 2012a and Dietze *et al.* 2016 for early Holocene examples in the region) and a thermokarst lake formation in ice-rich permafrost, i.e. a (shallow) thaw lake development (Grosse *et al.* 2013; Bouchard *et al.* 2017), respectively.

The question remains why the early Holocene wood was preserved for over ten millennia despite recently being exposed to the well-oxygenated and biologically active littoral zone of GSS. In general, wood above ground and in soil in temperate climates is mainly decomposed through fungi. At terrestrial and aquatic waterlogged sites, where oxygen is limited, bacteria have been determined as the primary degraders. In contrast to fungal decay, bacterial degradation is generally a slow process (Björdal *et al.* 1999). Experiments with exposed modern wood have shown that degradation still occurs to a certain extent in environments where oxygen is scarce (Jordan 1999; Fojutowski *et al.* 2014). But in the littoral zone of GSS, where the tree remains were found, oxygen is sufficiently available up to a water depth of (6-)8 m even during the thermal stratification in the summer (Kabus *et al.* 2004).

Similar to GSS, findings of well-preserved subfossil conifer wood (*Thuja occidentalis*, northern white-cedar) from the early Holocene were reported from the well-oxygenated bottom of Lake Huron, Canada (Larson & Melville 1996). Here, too, the wood was surprisingly well preserved. The authors reasoned that wood-decomposing bacteria must have either been absent in this environment or that yet unknown physical and/or chemical conditions within the wood prevented the growth of wood-decomposing organisms. Probably, the content and composition of resin contributed to the decay resistance of the conifer wood (e.g. Venäläinen *et al.* 2003).

The absence of bark indicates that the tree remains at GSS must have undergone some decay before becoming submerged and covered by gyttja. We cannot rule out that the trees were covered by thicker lacustrine sediments for a long time and only recently became exposed. The artificial formation of a stream inflow and the lake level drop in the 18th/19th century AD (Breitbach 2016) may have both increased subaquatic sediment erosion at the study site. However, further findings of subfossil Lateglacial to early Holocene conifers in the Baltic Sea (see below) and in lakes in northern Europe (e.g. Eronen *et al.* 1999; Gunnarson 2008; Kullman 2013), as well as in the Great Lakes region in North America (e.g. Chrzastowski *et al.* 1991; Larson & Melville 1996; Leavitt *et al.* 2006; Boyd *et al.* 2012), indicate that marine and freshwater environments are generally able to preserve trees for as long as 15 000 years.

Subfossil in situ pine occurrences in northern central Europe

Further subaquatic *in situ* tree remains were found in 2015 in nearby Lake Wittwesee and Lake Nehmitzsee, ~10-12 km southeast of GSS (Fig. 1A). In Wittwesee, Scots pine tree stumps (*Pinus sylvestris*) and birch (*Betula* spec.) were recorded at a depth of 4 m. In Nehmitzsee a pine stump was found at a depth of 6.6 m. The tree remains are older than in GSS, dating to the Lateglacial (Table 1, Table S1). Together with the findings at GSS, the records of pine stumps now span the age interval between 13 700 to 10 240 cal. a BP, i.e. about 3500 years. Regionally, the closest finds of old subfossil trees from a terrestrial site have been reported from Dobbertin, ~70 km to the northwest, with a pine trunk dating at about 12.8 cal. ka BP and *in situ* dwarf or shrubby birch (*Betula nana* or *B. humilis*) trunk dating at *c.* 14.2 cal. ka BP (Lorenz *et al.* 2015).

Whereas allochthonous pine wood from the Lateglacial and early Holocene has been repeatedly found in various sedimentary environments throughout central and northern Europe (e.g. Nicolussi & Patzelt 2000; Bos & Urz 2003; Nikonov & Rusakov 2010), contemporaneous *in situ* records of this species including forest soils are rare. These finds originate from terrestrial, peatbog, submerged marine and submerged lake records (Fig. 8A; Table S3). The most common finds mainly originate from sites in glacial landscapes of the North European Plain, which are covered by aeolian (Friedrich *et al.* 2001), fluvial (Dzieduszyńska *et al.* 2014) and telmatic sediments (Achterberg *et al.* 2016). All minerogenic terrestrial sites indicate a local shift from a stable landscape with soil formation and tree growth to intensified geomorphic dynamics with aeolian or fluvial sedimentation. According to the studies mentioned above, several reasons were identified for the death of the trees, including windthrow, groundwater rise, fire or sediment loading. The marine finds originate from the Baltic coast, where subfossil pines have been detected in 3 to 50 m water depth. The trees were partly found within well-preserved submerged landscapes with landforms and soils, as well as vegetational, faunal and Mesolithic anthropogenic remains (Fischer 1997; Hansson *et al.* 2017, 2018; Rosentau *et al.* 2017). Finds of Lateglacial and early Holocene subfossil pine trees in lakes of northern central Europe have so far been limited to the lakes reported in this paper.

The total of 83 radiocarbon ages from Lateglacial and early Holocene *in situ* pine trees reveal four age clusters centred around 12 700 cal. a BP (Allerød-Younger Dryas transition), 12 100 cal. a BP (early Younger Dryas), 10 700 cal. a BP (mid-Preboreal to early Boreal) and

8700 cal. a BP (late Boreal to Atlantic; Fig. 8B; Table S3). The largest number of dates per biozone is available for the late Atlantic, Younger Dryas and Preboreal. There is a clear relationship between sedimentological-taphonomical category (or geo-bio-archive) and age. The pines buried in peat date to the late Boreal to Atlantic cluster, while nearly all pines from the Baltic Sea and most of the pines from lakes belong to the mid-Preboreal to early Boreal age cluster. Most terrestrial occurrences date to the Allerød and Younger Dryas (Fig. 8B). The link between sedimentary environment and age can be traced even further to younger subfossil pines found in peatlands, which originated in the mid- and late Holocene (Edvardsson *et al.* 2016).

In sum, subfossil pine finds from the Lateglacial and early Holocene in northern central Europe and beyond document shifts of the zonal boreal forest ecosystem (Hytteborn *et al.* 2005) during the late Quaternary.

Conclusions

In situ subfossil trees offer a rare opportunity to connect past tree growth to a broad range of environmental variables such as soil, hydrology and general landscape evolution.

For the first time, evidence of a submerged pine forest from the early Holocene could be documented in a central European lake. This, alongside recently detected Lateglacial *in situ* tree occurrences in nearby lakes, constitutes a new and highly promising type of regional geo-bio-archive. The multi-proxy approach used to detect and characterise subfossil trees at Lake Giesenschlagsee leads to the following conclusions:

- Scuba diving proved to be the most efficient way for detecting, documenting and sampling subaquatic tree remains. Surveys by side-scan sonar and ROV provided additional help.
- In terms of age and taphonomic characteristics, the subfossil tree record comprises three categories dating from the early to the late Holocene.

Submerged *in situ* pine stumps were found up to a water depth of 5.2 m. They can be dated to a period of 11 090 to 10 240 cal. a BP (mid-Preboreal to early Boreal).

- The related forest soil is sedge peat, whose tilting indicates subsidence through local dead ice melting, inundating the area and preserving the trees for millennia.
- Dendrochronological analyses of the well-preserved wood revealed a great potential for inferring environmental and climatological information from tree ring characteristics. A systematic screening for more subfossil wood preserved in regional lakes may produce longer and more continuous chronologies covering larger parts of the late Quaternary.
- The record substantially enhances the understanding of local lake formation and palaeohydrology, and opens a new avenue for research on regional palaeoecology and dendrochronology.
- Comparable *in situ* pine finds occur at some terrestrial and marine sites in northern central Europe and beyond but partly differ in age. In general, they document shifts of the zonal boreal forest ecosystem during the late Quaternary.
- As the vegetation history, topography and lake formation in the formerly glaciated (Weichselian) areas of northern central Europe are widely similar, further drowned forests, at least in some of the many regional glacial lakes, can be expected.

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Table

Table 1: Radiocarbon data from Lake Giesenschlagsee and from submerged pine remains from two nearby lakes. Data calibration was performed with OxCal software version 4.2 (Bronk Ramsey 2009) using the IntCal 13 calibration curve (Reimer *et al.* 2013) and range of 2σ standard deviation for analysis.

Figures

Fig. 1. Geographical setting of the Lake Giesenschlagsee area. A. Central part of the Mecklenburg Lake District with location of Lake Giesenschlagsee and further sites with submerged *in situ* tree remains (Lakes Wittwesee and Nehmitzsee), as well as lake sediment records (Krey & Kloss 1990; Hackelbörger 1995; Homann *et al.* 2002; Brande 2003; Strahl 2005; Schwarz 2006; Küster *et al.* 2012). B. Local topography at Lake Giesenschlagsee. C. Northern basin of Lake Giesenschlagsee with detected tree remains, lake sediment cores and soil pits as well as subaquatic and terrestrial relief properties.

Fig. 2. Photographs of the Lake Giesenschlagsee record. A. Northern part of the lake. B. Diver sampling tree stump GSSC5. C. Divers with a sample (cross section) of tree stump

GSSC3. D. Cross section of tree stump GSSC3 in the lab (diameter: ~22 cm). E. Tree stump GSSC3 found *in situ* (height: ~50 cm) with coating of algae and molluscs (zebra mussel, *Dreissena polymorpha*). F. Outside appearance of tree stump GSSC3 in the lab (total view) with coating of molluscs (zebra mussel) and small cavity-like feeding traces (upper part). G. Outside appearance of tree stump GSSC3 in the lab (detail view). H. Operating ROV. I. Photograph of tree stump GSSC1 (height: ~45 cm) taken by the ROV. J. Photograph of tree stump GSSC1 (height: ~45 cm) taken by diver during documentation and sampling (photographs: A, C, D, F-H: K. Kaiser; B, E: S. Oldorff; I: C. Engelhardt; J: C. Breitbach).

Fig. 3. Dendrochronological data for wood samples GSSC3 and Trunk2 from Lake Giesenschlagsee (for the radiocarbon ages of the samples see Table 1). A. Annual ring width. B. Mean ring density. C. Maximum latewood density. All curves are aligned along cambial age. D. Radiographic images of the two samples illustrating the excellent wood preservation.

Fig. 4. Sediment profiles investigated at Lake Giesenschlagsee (for location see Fig. 1C). A. Lake sediment cores arranged according to water depth. A stump is schematically depicted showing its probable preservation in the deeper part of the littoral. B. Lake sediment core GSSB5 from the northern shore with geochronological and sedimentological data. C. Soil pit GSSB12 from the eastern shore (lower lake terrace) with geochronological and sedimentological data.

Fig. 5. Simplified pollen diagram GSSB5 from Lake Giesenschlagsee.

Fig. 6. Radiocarbon dates of early Holocene age from Lake Giesenschlagsee covering an age interval of *c.* 11 090 to 10 240 cal. a BP (equivalent to mid-Preboreal to early Boreal biozones).

Fig. 7. Conceptual model showing the record of submerged tree remains and their sedimentological-topographical traits as well as selected research devices at the shoreline of Lake Giesenschlagsee.

Fig. 8. Lateglacial and early Holocene *in situ* pine occurrences in northern central Europe and beyond. A. Distribution of records differentiated according to the present-day environmental setting of the sites. 1 = Lake Giesenschlagsee, this study; 2 = Lake Wittwesee, this study; 3 = Lake Nehmitzsee, this study; 4 = Baltic Sea-Lithuania, Damusyte *et al.* (2004); 5 = Baltic Sea-Poland, Uścinowicz (2014); 6 = Baltic Sea-southern Sweden-Stenshuvud, (Håkansson 1972, 1976); 7 = Baltic Sea-southern Sweden-Långören, Andrén *et al.* (2007); 8 = Baltic Sea-southern Sweden-Lövdalen, Andrén *et al.* (2007); 9 = Baltic Sea-Denmark-Store Belt, Fischer (1995); 10 = Rostocker Heide-Cliff, Kaiser (2004); 11 = Altdarss-ADO 39, Kaiser *et al.* (2006); 12 = Leusden, Rijksdienst voor het Cultureel Erfgoed (2017); 13 = Roderwolde, Woldring & Zomer (2009); 14 = Cottbus-Nord, Gautier (1999), Kühner *et al.* (1999), Spurk *et al.* (1999); 15 = Reichwalde, Friedrich *et al.* (2001); 16 = Warendorf, Kaiser *et al.* (2012b); 17 = Kozmin Las, Dzieduszyńska *et al.* (2014); 18 = Helvoirt-Zandhorst, Polak (1963); 19 = Baltic Sea-Kadet Channel, Westphal *et al.* (2014); 20 = Baltic Sea-Zingst, Westphal *et al.* (2014); 21 = Draved Mose, Tauber (1966); 22 = Peatlands NW Germany, Achterberg *et al.* (2016); 23 = Lubminer Heide, Janke (2002); 24 = Duvensee, Bokelmann *et al.* (1985). B. Temporal distribution (probability density function) of radiocarbon ages yielded from these sites using a calibration plot (each date is represented by a bar using the mean of the radiocarbon age and of the calibrated age, respectively).

Supporting Information

Fig. S1. Gauging record at Lake Giesenschlagsee for the period 1972 to 2014 (data: Landesamt für Umwelt Brandenburg).

Fig. S2: Conceptual model showing the development of the lake basin and of the submerged tree occurrence investigated.

Table S1. Tree remains recorded at Lake Giesenschlagsee.

Table S2. Sedimentological data of the profiles investigated from Lake Giesenschlagsee (abbreviations: LOI = Loss-On-Ignition, TOC = Total Organic Carbon, TIC = Total Inorganic Carbon).

Table S3. List of late Pleistocene and early Holocene *in situ* occurrences of pine in northern central Europe and beyond.

Sample ID.	Location	Northing	Easting	Depth below surface	Material dated	Lab. ID.	Radiocarbon age with SD	Age calibrated, 2σ, with SD	Age calibrated, 2σ, age range
		(Dec. degr.)	(Dec. degr.)	(m)			(a BP)	(cal. a BP)	(cal. a BP)
GSSC3	Giesenschlagsee	53.199228	12.848664	3.8	Wood (pine)	Poz-67569	9520±50	10 880±210	11 090-10 660
GSSC6	Giesenschlagsee	53.197846	12.848329	2.7	Wood (pine)	Poz-67570	9190±50	10 370±130	10 500-10 240
GSSC5A	Giesenschlagsee	53.198620	12.847871	2.4	Wood (conifer)	Poz-67572	9440±50	10 790±270	11 060-10 520
GSSB5	Giesenschlagsee	53.198997	12.848840	7.4	Wood (pine)	Poz-80954	9400±60	10 740±310	11 060-10 430
GSSB12	Giesenschlagsee	53.197759	12.851971	0.7	Wood (pine)	Poz-80955	225±30	160±160	310-0
Trunk2	Giesenschlagsee	53.198476	12.847878	2.5	Wood (pine)	Poz-80956	3710±30	4060±90	4150-3970
NES1	Nehmitzsee	53.128541	12.991808	6.6	Wood (pine)	Poz-80888	10 760±60	12 670±80	12 750-12 580
WIS4	Wittwesee	53.121027	12.942824	4.0	Wood (pine)	Poz-80889	11 670±60	13 530±170	13 700-13 350

Table S1. Tree remains recorded at Lake Giesenschlagsee.

ID	Item	Northing (Dec. degr.)	Easting (Dec. degr.)	Water depth (m)	Altitude (m a.s.l.)	Heigth[1], length (cm)	Diameter (cm)	Botanical det.	Remark
GSSC1	Tree stump	53.199043	12.849871	4.2	52.6	45	20	-	-
GSSC2A	Tree stump	53.199043	12.848898	4.8	52.0	32	25	-	-
GSSC2B	Tree stump	53.199043	12.848898	5.2	51.6	15	20	-	-
GSSC3	Tree stump	53.199228	12.848664	3.6	53.2	30	25	Pine	Radiocarbon dating available
GSSC4A	Tree stump	53.198915	12.847766	2.4	54.4	15	8	-	-
GSSC4B	Tree stump	53.198915	12.847766	2.4	54.4	15	20	-	-
GSSC5A	Tree stump	53.198620	12.847871	2.4	54.4	10	25	Conifer	Radiocarbon dating available
GSSC5B	Tree stump	53.198620	12.847871	2.4	54.4	15	8	-	-
GSSC6	Tree stump	53.197846	12.848329	2.0	54.8	15	20	Pine	Radiocarbon dating available
GSSC7	Tree stump	53.197569	12.848447	2.2	54.6	7	50	Conifer	with (pre)historic surface cut
Trunk1	Tree trunk	53.198824	12.847726	3.0	53.8	350	30	-	-
Trunk2	Tree trunk	53.198476	12.847878	2.5	54.2	150	13	Pine	Radiocarbon dating available
GSSB5	Sediment core	53.198997	12.848840	7.5	50.8	-	-	Pine	Radiocarbon dating available
GSSB12	Soil pit	53.197759	12.851971	-	58.5	-	-	Pine	Radiocarbon dating available

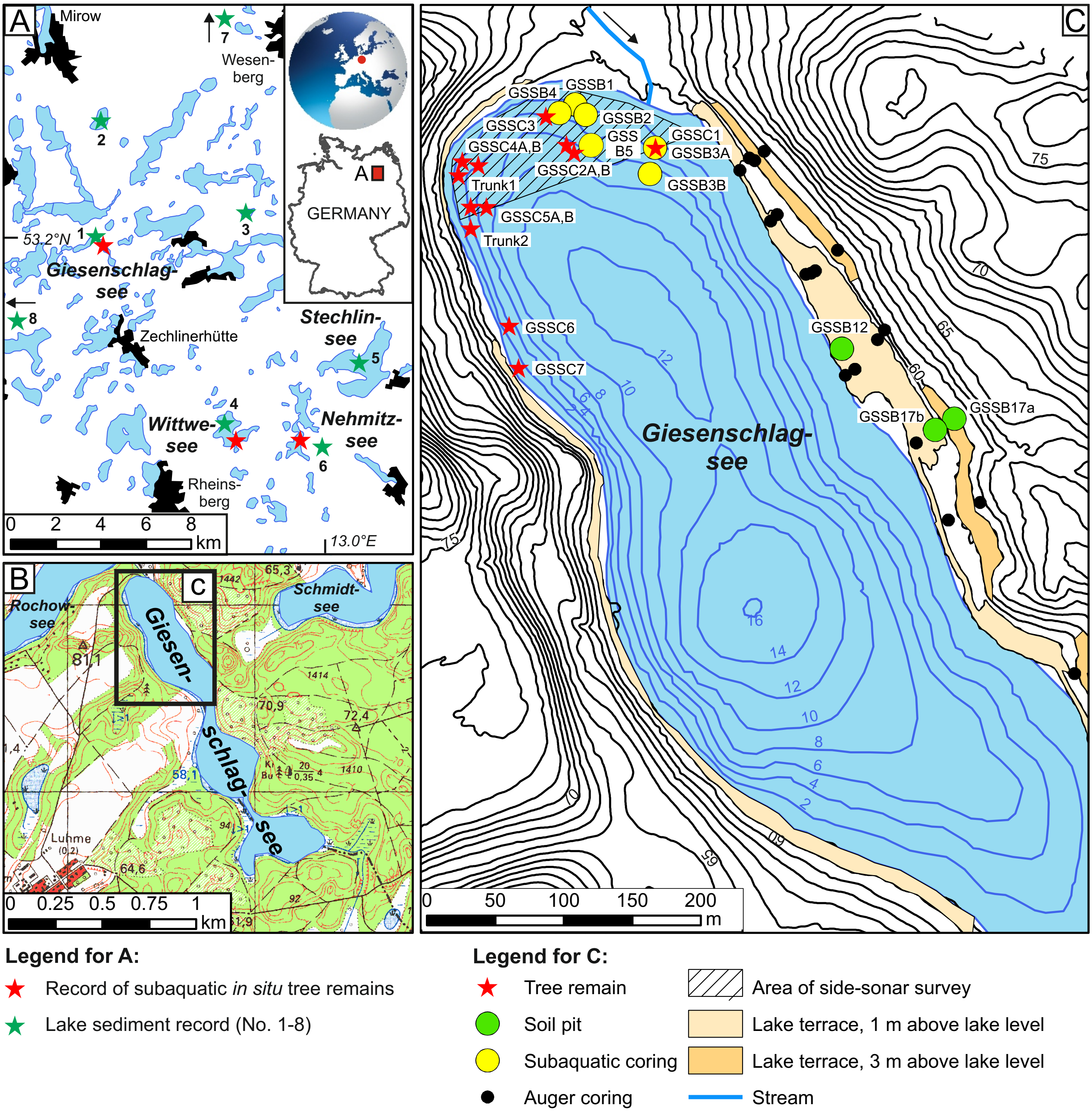
[1]above the current lake bottom

Table S2. Sedimentological data of the profiles investigated from Lake Giesenschlagsee (abbreviations: LOI = Loss-On-Ignition, TOC = Total Organic Carbon, TIC = Total Inorganic Carbon).

Profile	Northing	Easting	Sampling depth	Sediment classification	Pedological horizon	LOI	TOC	TIC	Grain-size composition				
									Clay+Silt <0.063 mm	Fine sand <0.2 mm	Medium sand <0.63 mm	Coarse sand <2 mm	Gravel >2 mm
	(Dec. degr.)	(Dec. degr.)	(cm)		(KA5)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
GSSB5	53.198997	12.848840	685-687	Gyttja	F	85.5	36.6	9.1	-	-	-	-	-
			700-702	Gyttja	F	87.2	40.4	7.4	-	-	-	-	-
			715-717	Gyttja	F	84.8	47.0	0.4	-	-	-	-	-
			721-723	Gyttja	F	29.4	20.9	0.8	-	-	-	-	-
			727-729	Gyttja	F	89.0	38.6	14.7	-	-	-	-	-
			730-732	Peat	IIfHr	88.8	50.0	2.9	-	-	-	-	-
			740-742	Peat	IIfHr	82.1	45.9	11.0	-	-	-	-	-
			752-754	Peat	IIfHr	50.8	14.0	0.0	-	-	-	-	-
			757-762	Lacustrine sand	IIIGr	1.0	0.3	0.0	11.8	24.4	48.8	10.2	4.7
GSSB12	53.197759	12.851971	0-30	Lacustrine sand	Go-Ah	2.4	1.1	0.0	4.5	38.2	47.0	8.0	2.4
			30-72	Lacustrine sand	Go	0.5	0.1	0.0	9.1	49.4	36.0	3.9	1.6
			72-84	Mixture lacustr. sand and peat	IIGo+fHr	17.9	6.0	0.7	-	-	-	-	-
			84-118	Peat	IIIfHr	92.1	35.1	19.0	-	-	-	-	-
			118-122	Gyttja	IVfF	29.3	44.3	3.5	-	-	-	-	-
			122-145	Peat	VfHr	37.8	14.0	2.2	-	-	-	-	-
			145-160	Gyttja	VIfF	17.2	2.9	0.1	-	-	-	-	-

Table S3. List of late Pleistocene and early Holocene *in situ* occurrences of pine in northern central Europe and beyond.

ID	Site	Northing (Dec. degr.)	Easting (Dec. degr.)	Present-day environment	Dated tree individuals (*n*)	Radiocarbon age (a BP)	Reference
1	Lake Giesenschlagsee	53.199041	12.84873	Subaquatic (freshwater)	3	9190±50, 9440±50, 9550±50	this study
2	Lake Wittwesee	53.121027	12.942824	Subaquatic (freshwater)	1	11 670±60	this study
3	Lake Nehmitzsee	53.128541	12.991808	Subaquatic (freshwater)	1	10 760±60	this study
4	Baltic Sea-Lithuania	56.054260	20.788236	Subaquatic (marine)	1	9160±60	Damusyte *et al.* 2004
5	Baltic Sea-Poland	54.911828	17.395787	Subaquatic (marine)	1	9430±50, 9580±50 (two ages from one tree)	Uścinowicz 2014
6	Baltic Sea-southern Sweden-Stenshuvud	55.419996	14.292291	Subaquatic (marine)	6	9100±120, 9330±95, 9420±95, 9420±100, 9520±95, 9620±95	Håkansson 1972, 1976
7	Baltic Sea-southern Sweden-Långören	56.011152	15.662877	Subaquatic (marine)	3	9300±130, 9380±90, 9400±110	Andrén *et al.* 2007
8	Baltic Sea-southern Sweden-Lövdalen	55.899295	14.367030	Subaquatic (marine)	2	9450±90, 9590±90	Andrén *et al.* 2007
9	Baltic Sea-Denmark-Store Belt	55.454322	10.860914	Subaquatic (marine)	2	8970±130, 9150±130	Fischer 1995
10	Rostocker Heide-Cliff	54.242020	12.196348	Terrestrial	1	11 220±250	Kaiser 2004
11	Altdarss-ADO 39	54.400132	12.526083	Terrestrial	1	10 680±60	Kaiser *et al.* 2006
12	Leusden	52.101375	5.338939	Terrestrial	0	no data (Lateglacial)	Rijksdienst voor het Cultureel Erfgoed 2017
13	Roderwolde	53.180611	6.465019	Terrestrial (bog)	6	7830±25, 7915±30, 7900±30, 7920±20, 8130±60, 8370±25	Woldring & Zomer 2009
14	Cottbus-Nord	51.786338	14.419326	Terrestrial	7	10 100±70, 10 220±65, 10 320±70, 10 215±70, 10 282±26, 10 310±45, 10 148±84	Gautier 1999; Kühner *et al.* 1999; Spurk *et al.* 1999
15	Reichwalde	51.397279	14.694036	Terrestrial	3	11 522±33, 11 890±31, 12 039±49	Friedrich *et al.* 2001
16	Warendorf	51.964101	7.948489	Terrestrial	3	10 105±40, 11 121±24, 11 617±33	Kaiser *et al.* 2012b
17	Kozmin Las	52.094942	18.651510	Terrestrial	16	10 310±90, 10 480±50, 10 570±50, 10 570±50, 10 580±50, 10 650±60, 10 660±50, 10 700±60, 10 710±50, 10 710±60, 10 730±60, 10 780±80, 10 830±70, 10 900±50, 10 940±50, 11 260±70	Dzieduszyńska *et al.* 2014
18	Helvoirt-Zandhorst	51.645211	5.223610	Terrestrial	0	no data (Allerød palynozone)	Polak 1963
19	Baltic Sea-Kadet Channel	54.527262	12.303254	Subaquatic (marine)	6	9290±60, 9330±50, 9430±60, 9460±50, 9766±67, 9840±50	Westphal *et al.* 2014
20	Baltic Sea-Zingst	54.463435	12.821818	Subaquatic (marine)	1	11 080±60	Westphal *et al.* 2014
21	Draved Mose	55.013168	8.972927	Terrestrial (bog)	4	7370±150, 7590±150, 7790±140, 7810±140	Tauber 1966
22	Peatlands NW Germany	53.037990	7.637002	Terrestrial (bog)	16	7330±50, 7360±55, 7420±60, 7675±45, 7680±50, 7705±50, 7710±45, 7710±60, 7725±45, 7725±50, 7900±60, 7910±50, 7935±45, 7950±50, 7975±45, 8670±50	Achterberg *et al.* 2016
23	Lubminer Heide	54.142383	13.657219	Terrestrial	0	no data (but Allerød age; related peat bed was radiometrically dated)	Janke 2002
24	Duvensee	53.691551	10.566393	Terrestrial (bog)	1	8660±80	Bokelmann *et al.* 1985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Legend for C:
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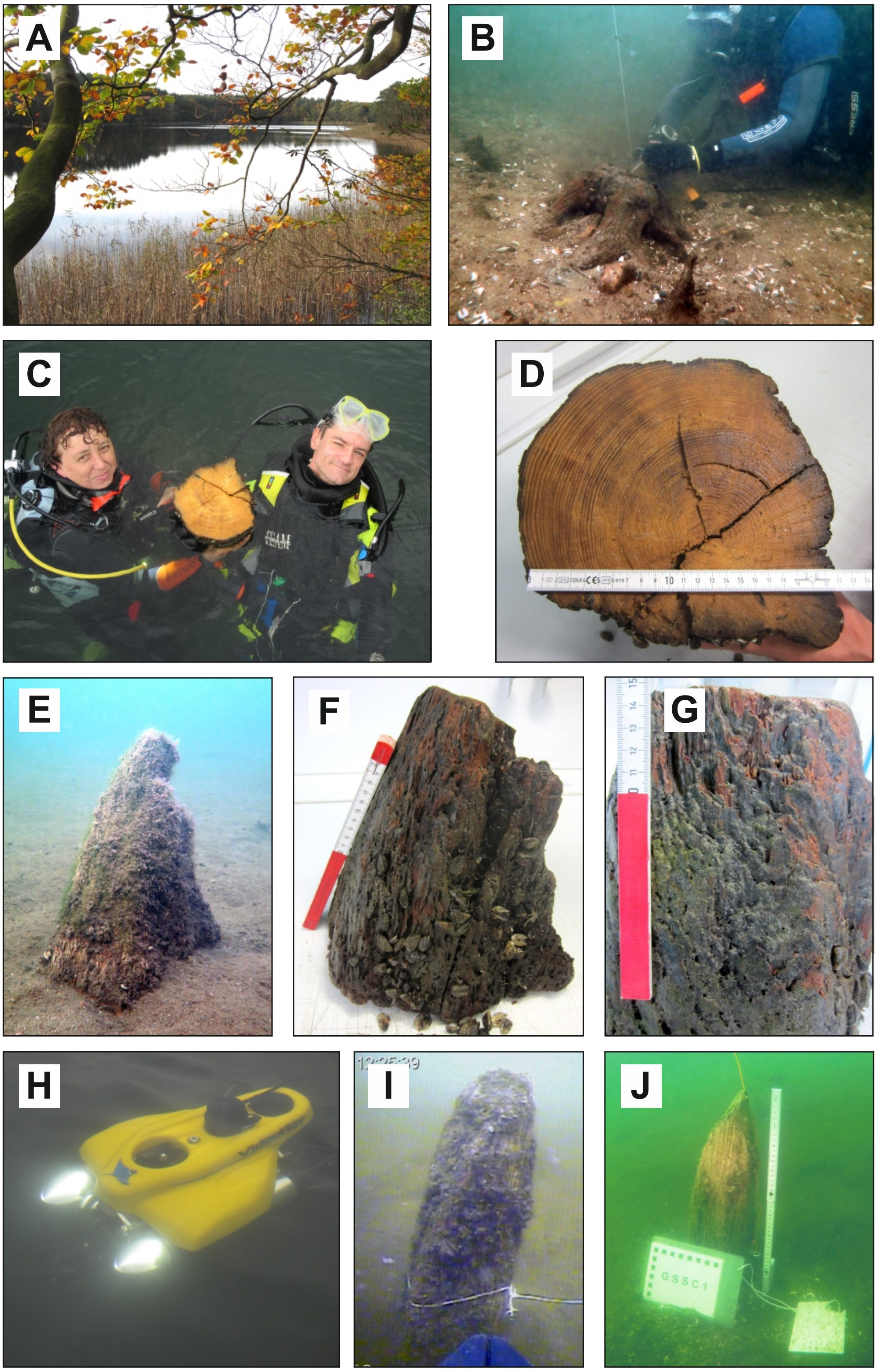
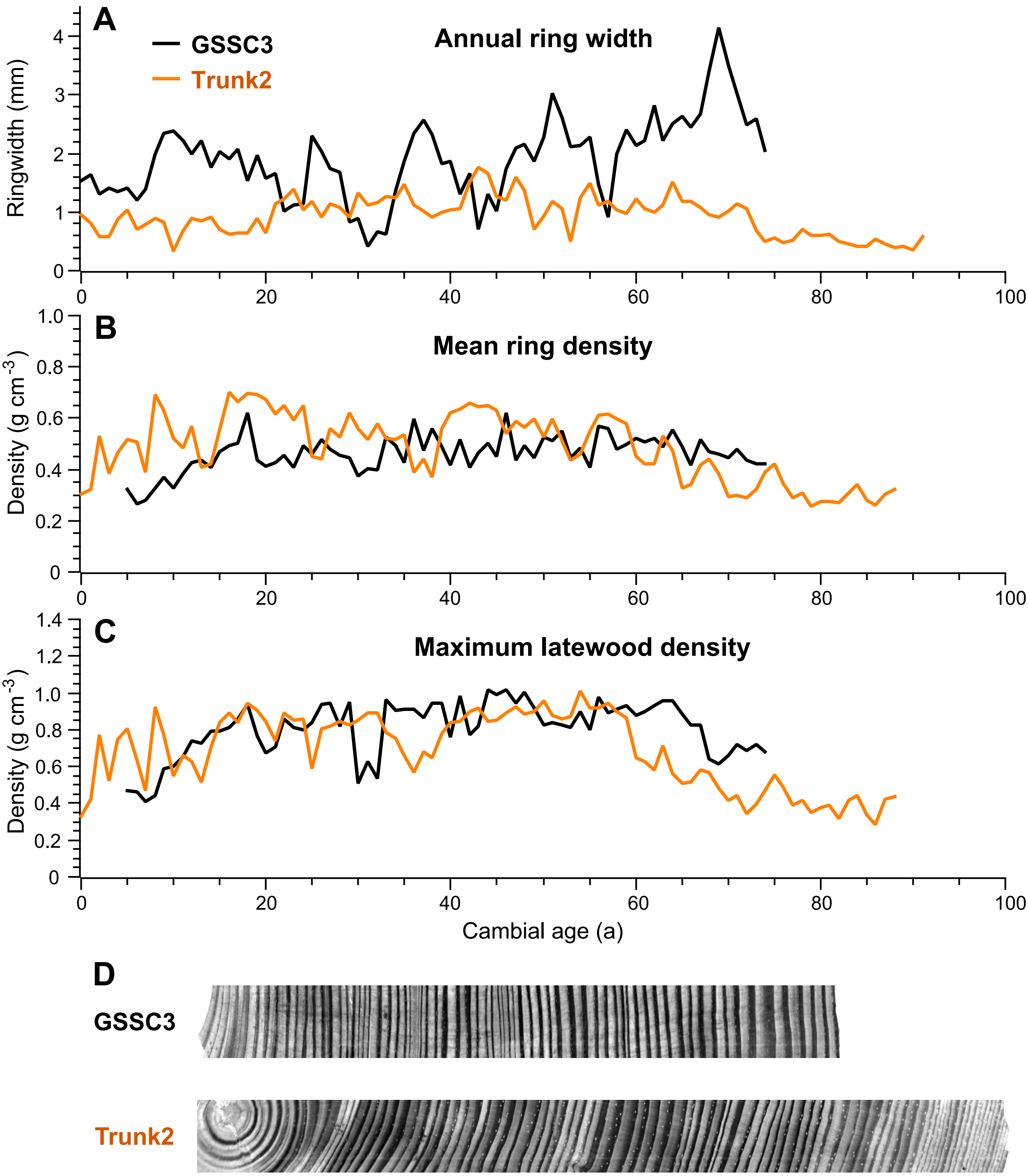
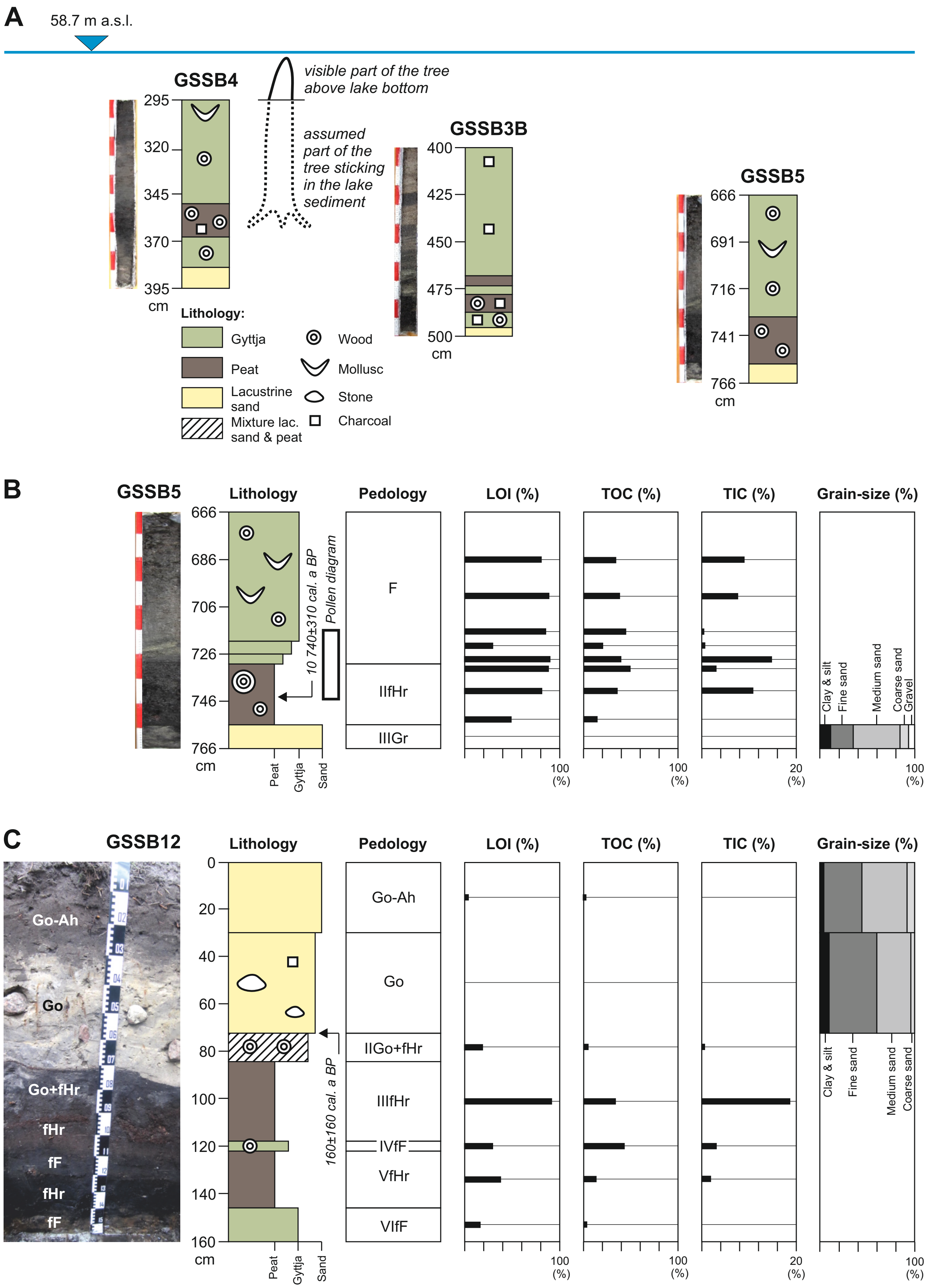
Soil pit
Subaquatic coring
Auger coring
Area of side-sonar survey
Lake terrace, 1 m above lake level
Lake terrace, 3 m above lake level
Stream

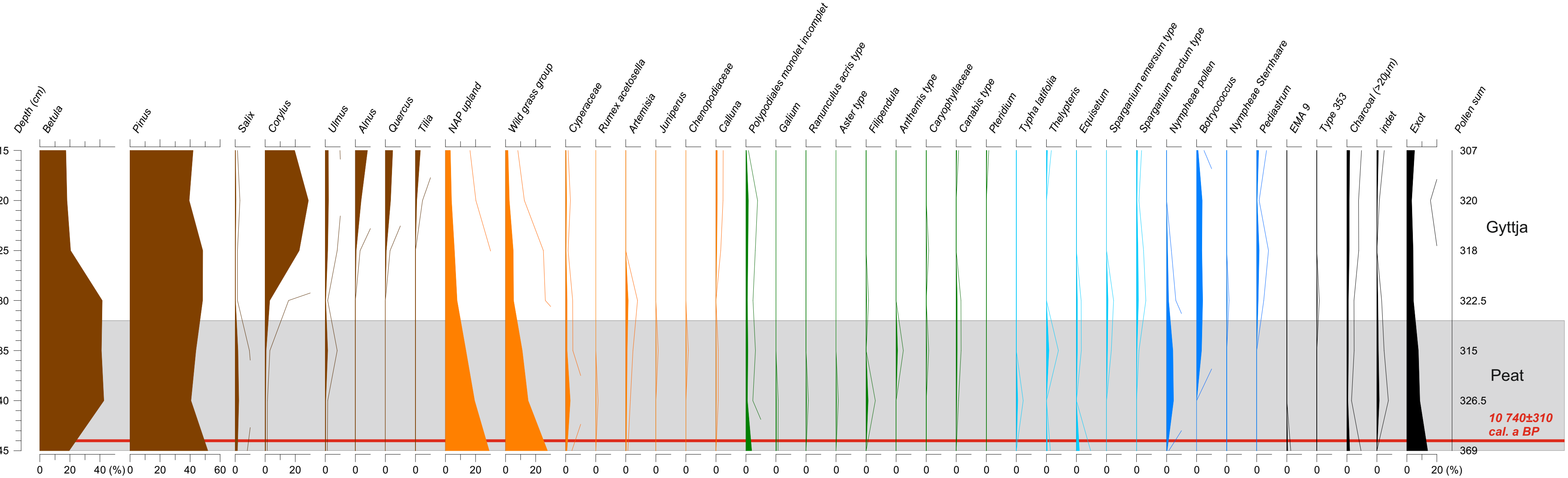

A
B
C
D
E
F
G
H
I
J



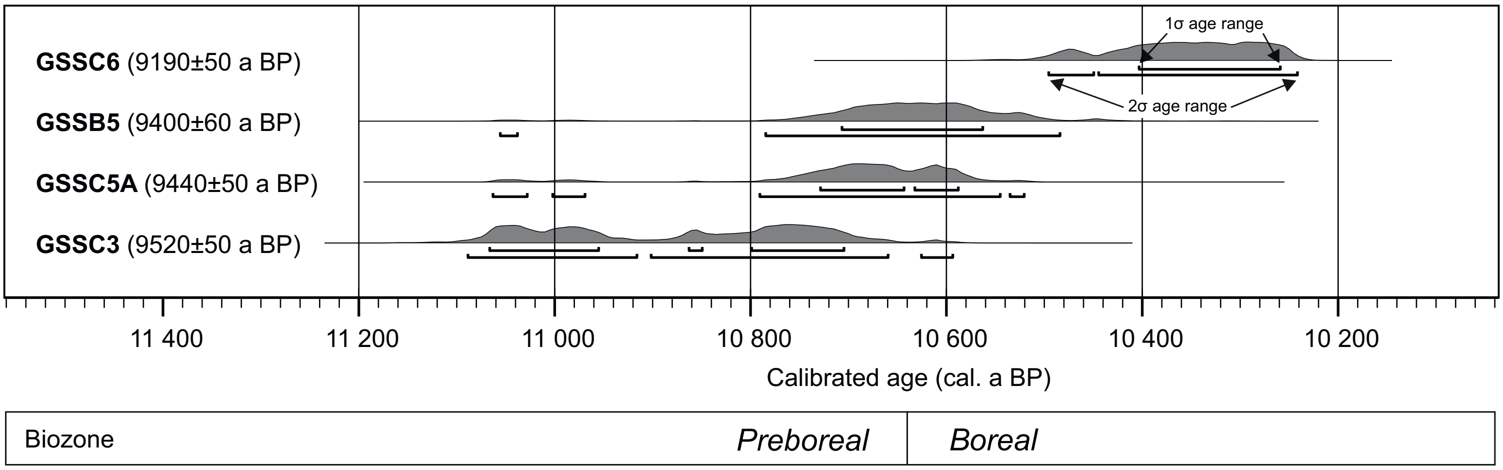
A
GSSC3
Trunk2
Annual ring width
Ringwidth (mm)
B
Mean ring density
Density (g cm-3)
C
Maximum latewood density
Density (g cm-3)
Cambial age (a)
D
GSSC3
Trunk2



A
58.7 m a.s.l.
GSSB4
295
320
345
370
395
cm
visible part of the tree above lake bottom
assumed part of the tree sticking in the lake sediment
GSSB3B
400
425
450
475
500
cm
GSSB5
666
691
716
741
766
cm
Lithology:
Gyttja
Peat
Lacustrine sand
Mixture lac. sand & peat
Wood
Mollusc
Stone
Charcoal
B
GSSB5
Lithology
Pedology
LOI (%)
TOC (%)
TIC (%)
Grain-size (%)
666
686
706
726
746
766
cm
10 740±310 cal. a BP
Pollen diagram
Peat
Gyttja
Sand
F
IIfHr
IIIGr
100 (%)
100 (%)
20 (%)
100 (%)
Clay & silt
Fine sand
Medium sand
Coarse sand
Gravel
C
GSSB12
Go-Ah
Go
Go+fHr
fHr
fF
fHr
fF
Lithology
Pedology
LOI (%)
TOC (%)
TIC (%)
Grain-size (%)
0
20
40
60
80
100
120
140
160
cm
160±160 cal. a BP
Peat
Gyttja
Sand
Go-Ah
Go
IIGo+fHr
IIIfHr
IVfF
VfHr
VIfF
100 (%)
100 (%)
20 (%)
100 (%)
Clay & silt
Fine sand
Medium sand
Coarse sand



Depth (cm)
Betula
Pinus
Salix
Corylus
Ulmus
Alnus
Quercus
Tilia
NAP upland
Wild grass group
Cyperaceae
Rumex acetosella
Artemisia
Juniperus
Chenopodiaceae
Calluna
Polypodiales monolet incomplet
Galium
Ranunculus acris type
Aster type
Filipendula
Anthemis type
Caryophyllaceae
Canabis type
Pteridium
Typha latifolia
Thelypteris
Equisetum
Sparganium emersum type
Sparganium erectum type
Nympheae pollen
Botryococcus
Nympheae Sternhaare
Pediastrum
EMA 9
Type 353
Charcoal (>20µm)
indet
Exot
Pollen sum
715
720
725
730
735
740
745
307
320
318
322.5
315
326.5
369
Gyttja
Peat
10 740±310
cal. a BP
0 20 40 (%)
0 20 40 60
20 (%)


GSSC6 (9190±50 a BP)
GSSB5 (9400±60 a BP)
GSSC5A (9440±50 a BP)
GSSC3 (9520±50 a BP)
1σ age range
2σ age range
11 400
11 200
11 000
10 800
10 600
10 400
10 200
Calibrated age (cal. a BP)
Biozone
Preboreal
Boreal

Sediment / wood

- Sand
- Peat
- Gyttja
- Pine tree remains

Pine tree remains

- (1) Early Holocene tree stump rooting in sandy ground
- (2) Late Holocene tree trunk lying on the lake bottom
- (3) Early Holocene tree stump rooting in peaty ground

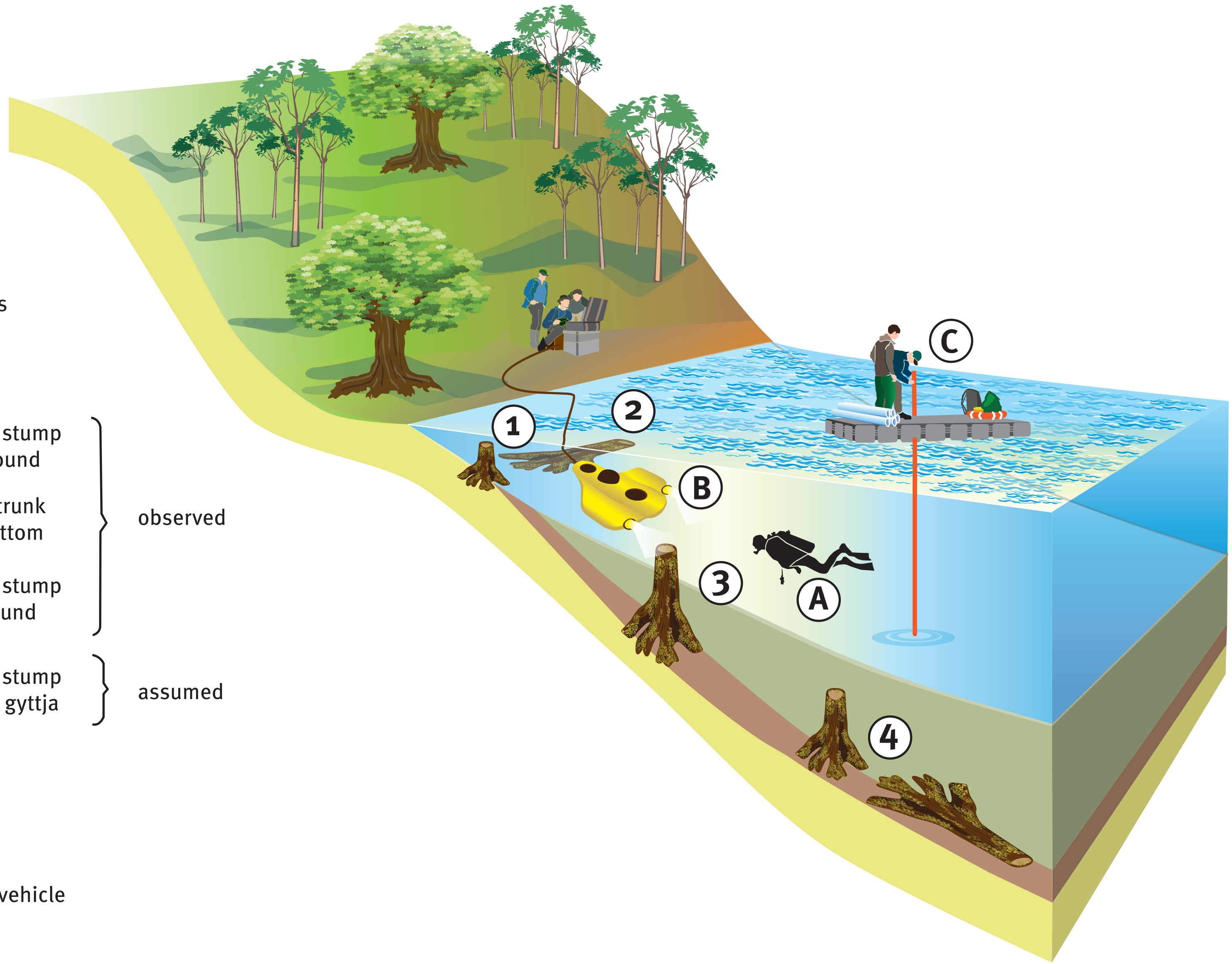
}observed

- (4) Early Holocene tree stump and trunk buried by gyttja

}assumed

Research devices

- (A) Scuba diver
- (B) Remotely operated vehicle
- (C) Coring from a raft



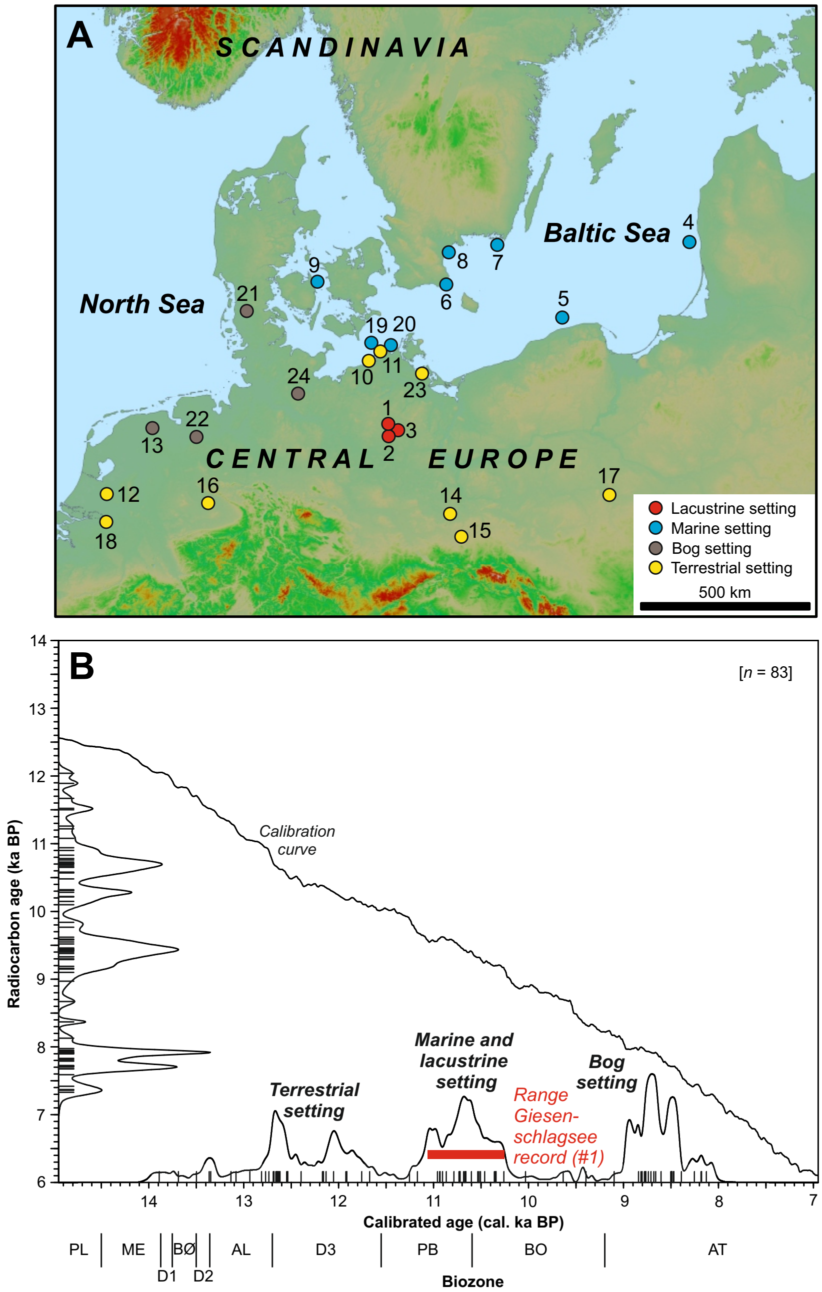

A
SCANDINAVIA
Baltic Sea
North Sea
CENTRAL EUROPE
Lacustrine setting
Marine setting
Bog setting
Terrestrial setting
500 km
B
[n = 83]
Calibration curve
Radiocarbon age (ka BP)
Terrestrial setting
Marine and lacustrine setting
Bog setting
Range Giesen-schlagsee record (#1)
Calibrated age (cal. ka BP)
PL
ME
BØ
D1
D2
AL
D3
PB
BO
AT
Biozone

Fig. S1. Gauging record at Lake Giesenschlagsee for the period 1972 to 2014
(data: Landesamt für Umwelt Brandenburg).

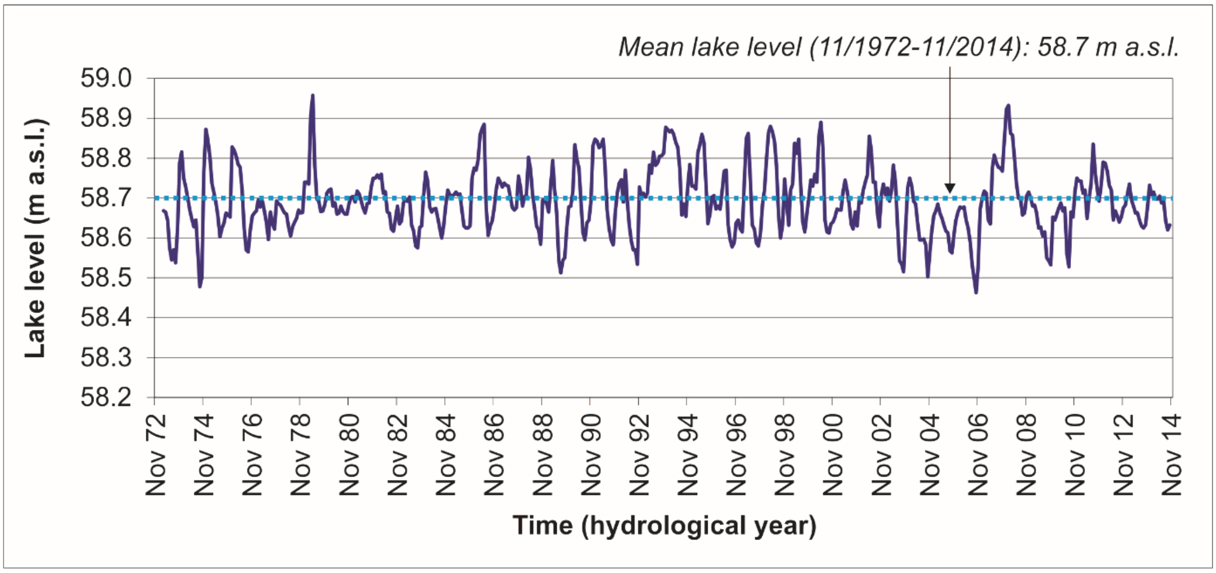


Fig. S2. Conceptual model showing the development of the lake basin and of the submerged tree occurrence investigated.