Early historical forest clearance caused major degradation of water quality at Lake Væng, Denmark

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ABSTRACT

Although humans have impacted their environment over millennia, details of these impacts, especially on aquatic systems, is still surprisingly scarce despite potential disturbance by early land use. This study examined a high-resolution radiocarbon-dated Holocene record from the Danish Lake Væng, using geochemical and biological proxies, and related the observed impacts to other lake records with catchment disturbance. The results indicate a lengthy and varying history of aquatic eutrophication linked to human activity. Modest impacts on the lake coincided with the first signs of landscape disturbance during the Neolithic (c. 4500 cal. yrs BP). Observed impacts intensified in the Late Bronze and Pre-Roman Iron Age. Viking Age/Medieval deforestation and erosional inputs to the lake associated with new ploughing technology (1200 cal. yrs BP), however, led to a major reorganisation of the aquatic ecosystem. Filamentous bloom-forming cyanobacteria, common today in heavily culturally impacted lakes, reached a historical maxima. The lake ecosystem subsequently recovered somewhat but remains eutrophic to date. The erosion record from Lake Væng shows a striking similarity with other Danish lake records, especially the notable increase in Medieval Period catchment inputs, which are observed in other European lacustrine records. Numerous European lowland lakes may have shifted into a degraded ecological state millennia ago, but degradation intensified during the onset of the Medieval Period. Hence, assuming pre-industrial conditions as relatively pristine reference baselines for more recent cultural eutrophication could be flawed in landscapes intensively used by humans for millennia.

Keywords: Catchment-lake processes; macrofossils; pigments; inorganic phosphorus; soil erosion; Holocene

1. Introduction

Humans have altered their surrounding landscapes for sustenance since the Early Holocene (Harris, 1996). As agriculture and the associated clearance of forests became more widespread, surface soil erosion increased markedly. Globally, human-driven soil erosion became significant around 4000 years ago (Jenny et al., 2019). While a wealth of palaeoecological evidence exists on past climate, landscape disturbance and associated soil erosion, much less is known on early human-induced changes in the structure and functioning of aquatic ecosystems. Lake ecological status is, however, known to potentially be affected by increased soil erosion via the enhanced external loading of sediment and nutrients, causing increased turbidity and eutrophication (Dubois et al., 2018; Jenny et al., 2019 and references therein).

Proxy-based climate reconstructions for Northwest Europe invariably report a pattern of increasing Early Holocene temperatures, a Mid-Holocene thermal maximum and decreasing temperatures during the last 4000 years (Brown et al., 2012; Mauri et al., 2015). Seasonal differences in humidity were more pronounced during the Mid-Holocene with slightly depressed summer rain and marginally higher winter precipitation (Mauri et al., 2015). This humidity pattern is corroborated by a raised bog record from Svanemose, in southern Jutland (Denmark), which shows more dry conditions between 4000 and 2500 BP, increasing humidity towards a peak at

1400-800 BP followed by a drier period since then (Barber et al., 2004). Such climate change patterns could potentially have resulted in variable nutrient loading to lake basins through effects on surface erosion. In the central European area, however, 6000–7000 years of farming have resulted in massive and increasing disturbance of land cover, hydrology, erosion regimes and even climate itself. These disturbances have generally over-ridden the more subtle effects of climate change on lake ecological status (Smith et al., 2016; Wang et al., 2017; Zanon et al., 2018).

The lowland lakes of northwest continental Europe located in such heavily impacted cultural landscapes have been subject to increased anthropogenic disturbance since at least 6000 yr BP (e.g., Kalis et al., 2003; Boyle et al., 2015). Presently, it is estimated that *c.* 60% of European waterbodies are disturbed beyond good ecological status (EEA, 2018). Hence, a wealth of studies has investigated eutrophication, and how lake system structure and functioning have responded to intensive modern agricultural practices and urbanisation in recent centuries (e.g., Lotter, 1998; Langdon et al., 2006; Bennion and Simpson, 2011; Anderson et al., 2014). Far fewer, however, have focused on the impact of early land use on lakes over millennia (Fritz, 1989; Bradshaw et al., 2005). Studies of early human impacts can help to resolve debates about how, where and whether humans significantly changed their environment (Ruddiman, 2013; Lewis and Maslin, 2015; ArchaeoGLOBE Projec; 2019). Multi-evidence (multi-proxy) palaeoecological investigations have the unique potential to provide insights into past landscape and lake disturbance and help understand the process of lake eutrophication.

Studies of Holocene environmental changes in Denmark over more than 150 years have revealed how humans have cleared the forests of Denmark, starting in the Early Neolithic (*c.* 5900–5200 cal. yr BP; Iversen, 1973). A number of Danish lakes have exceptionally high sedimentation rates (e.g., Rasmussen and Anderson, 2005; Bradshaw et al., 2005), allowing for highly temporal resolution analysis of lake system changes in the past. Lake Væng, the site of this study, has accumulated almost 18 m of sediment during the Holocene.

A recent extensive review of first human impacts on aquatic systems stated that, while human impacts at the landscape level are relatively easy to detect, the effects of human disturbance on aquatic ecosystems need further investigation. While case studies exist, they are often based on one aquatic proxy (e.g., diatom assemblages) and hence provide a limited view of lake ecosystem change (Dubois et al., 2017 and references therein). This study investigates the entire Holocene development of Lake Væng, to encompass variability in the pre-disturbance 'natural' state. We reconstruct erosion intensity and lake response at a high temporal resolution, to detect and assess changes in nutrient dynamics, and algae, cyanobacteria, invertebrate and fish communities. In doing so, we aim to answer the following questions: 1) When was the lake first impacted by human activity? 2) Which time periods witnessed the most intensive impacts, and what was the ecosystem response? 3) How do these changed ecosystem states compare to modern lake conditions? 4) How quickly did the lake respond to external sediment and nutrient loading and was the response proportional to the external forcing? By exploring these questions, we gain new insights into the impacts of early human-induced landscape changes on aquatic ecosystems.

2. Study site

Lake Væng is located in eastern Jutland, east of the most extended ice marginal position of the Scandinavian Ice Sheet during the Last Glacial Maximum (Fig. 1). The region was deglaciated about 18 000–19 000 years ago according to cosmogenic surface exposure dating of large erratic boulders (Houmark-Nielsen et al., 2012). The lake has a surface area of 15.7 ha, a mean and maximum water depth of 1.2 m and 1.9 m and a water table at 26.3 m above sea level. The shallow lake is located in a northwest–southeast orientated valley with peat deposits in an area dominated by glaciofluvial sandy deposits and Miocene sandy and coal-bearing fluvial and deltaic deposits (Kidmose et al., 2013). The area close to the lake is mainly forested, but the forests are only some decades old and mainly consist of coniferous plantations. Studies of historical maps show that agricultural land dominated the area a hundred years ago (Fig. 1; https://historiskatlas.dk/). The topographical catchment is 9.8 km^2 (Kidmose et al., 2013).

Three small inlets contribute water to the lake, but groundwater comprises 74% of the water entering the lake (Kazmierczak et al., 2016). An outlet is also present at the south end of the lake. The climate of the region is temperate, with a mean July air temperature of *c.* 15.4 °C and mean annual precipitation of *c.* 780 mm during the period from 1961 to 1990. The lake's residence time is relatively short, about three weeks (Kidmose et al., 2013).

Lake Væng is a eutrophic and turbid lake, where groundwater-controlled input of dissolved inorganic phosphorus (DIP) is one of the factors maintaining eutrophic conditions (Kidmose et al., 2013; Kazmierczak et al., 2020). Previous studies (Kidmose et al., 2013; Kazmierczak et al., 2020) have indicated that the origin of DIP discharged via groundwater is geogenic. Total phosphorus (TP) concentrations in the lake water varied between 36 and 196 µg L^{-1} during the period of 1985–2015 (Meijer et al., 1994; Søndergaard et al., 1990, 2017). The mean summer concentration of TP in the water was reduced from about 120 µg L^{-1} in 1986 to 60 µg L^{-1} in 1989 and to 50 µg L^{-1} in

2011 as a result of bio-manipulations involving removal of zooplanktivorous and benthivorous fish (Søndergaard et al., 1990, 2017; Jeppesen et al., 2012). The secchi depth increased from *c.* 60 cm in 1986 to *c.* 170 cm in 2011 and submerged macrophytes spread over the lake bottom. These observed improvements in water quality, however, lasted only a few years (Meijer et al., 1994; Søndergaard et al., 1990, 2017). The geographical coordinates at the coring site are 56°2.17´N, 9°39.32´E and the water depth was 175 cm.

3. Methods

3.1. Field work

Coring was carried out from a Uwitec coring platform. We used a Kajak corer (Renberg, 1991) to sample the surface sediment (down to 40 cm), a Russian peat corer (Jowsey, 1966) to sample the upper sediments and a Usinger piston corer (Mingram et al., 2007) to sample the deeper parts of the sediment sequence in the lakes. The Russian corer had a chamber length of 1 m and a diameter of 7.5 cm. We used 2 m long 8 cm diameter coring tubes for the Usinger corer. Two parallel Usinger cores, labelled A and B were retrieved. In the deepest parts of the coring, the corer was hammered down using a percussion hammer. The Kajak samples were extruded and subsampled in the field whereas the Russian cores were transferred to half-tubes, packed and brought to the laboratory. The Usinger cores were extruded, cut into 1 m long sections, transferred to plastic tubes, packed and brought to the laboratory where the cores were split length wise.

3.2. ITRAX scanning

We analysed the cores using an ITRAX X-ray fluorescence (XRF) core scanner to measure elemental variations (Croudace et al., 2006). A Rhodium (Rh) tube with a resolution of 5 mm provided XRF scans. The voltage and current were set to 30 kV and 50 mA, respectively, with an XRF count time of 60 seconds. X-ray line-scan images were obtained in 1 mm resolution using a tube setting of 60 kV and 30 mA and 1000 ms exposure time. The ITRAX core scanner is equipped with an optical camera for high resolution digital line-scan images, as well as a Bartington magnetic susceptibility detector used in 4 mm resolution. The XRF data were used for core correlations, as a record of soil erosion (titanium, Ti) and to trace sediment hypoxia/anoxia (iron/manganese ratio, Fe/Mn).

Core correlations were performed using a Matlab program developed by Rasmussen (2006). Stratigraphic markers were found in the records of Fe, Zirkonium (Zr), radiography grey scale, magnetic susceptibility and the coherent/incoherent scatter ratio. The Usinger A and B cores were correlated using 123 correlation points (Supplementary).

3.3. *Inorganic phosphorus and loss-on-ignition*

We determined inorganic phosphorus by extraction in 1 M HCl (16 h, 1:50 solid to solution ratio) with detection by molybdate colorimetry (Murphy and Riley, 1962) following neutralization with dilute NaOH. The procedure primarily extracts phosphate associated with calcium (i.e. apatite or secondary carbonates), as well as soluble phosphate and phosphate sorbed to secondary metal oxides.

Loss-on-ignition (LOI) was determined by quantifying mass loss following combustion at 550°C for 4 hours. We first dried samples at 105°C for 24 hours to remove water. Values for all procedures are expressed on an oven-dry (105°C × 24 h) mass basis.

3.4. Macrofossils and radiocarbon dating

ITRAX scanning of the cores was followed by visual sediment descriptions and subsampling of the cores. Contiguous samples were taken for macrofossil analyses, except for the bottom part of the Lake Væng succession. We could not extrude the bottom part because the sediments were too stiff. Hence, we had to dig out samples from the core tube. The samples were wet sieved on 0.4 and 0.2 mm sieves and the residue left on the sieves transferred to a petri dish and analysed using a Leica Wild M3C dissecting microscope. A total number of 414 samples was analysed. Selected remains of terrestrial plants from 16 levels were submitted for accelerator mass spectrometry radiocarbon dating at the Aarhus AMS ^{14}C Centre (Table S1). The widespread occurrence of carbonate-rich glacial deposits in Denmark results in large hard-water effects, and hence selecting remains of terrestrial plants for dating is important. Calibration to calendar years is according to the INTCAL20 data (Reimer et al., 2020). The age-depth model was generated using OxCal version 4.3 (Bronk Ramsey, 2013).

3.5. Chlorophyll and carotenoid pigments

Pigments were quantitatively extracted in an acetone: methanol: water (80:15:5) mixture. Extracts were left overnight at –10 ºC, filtered with a PTFE 0.2 μm filter and dried under nitrogen gas. A known quantity was re-dissolved into an injection solution of a 70:25:5 mixture of acetone: ion-pairing reagent (IPR; 0.75 g of tetra butyl ammonium acetate and 7.7 g of ammonium acetate in 100 mL water): methanol and injected into the HPLC unit. Separations used an Agilent 1200 series module with quaternary pump. The mobile phase comprised solvent A (80:20 methanol: 0.5 M ammonium acetate), solvent B (9:1 acetonitrile: water) and solvent C (ethyl acetate) with the stationary phase consisting of a Thermo Scientific ODS Hypersil column (205 × 4.6 mm; 5 µm particle size). The separation conditions started with 100% solvent A and ramped to 100% solvent B over 4 minutes, followed by a linear increase towards 75% solvent C for 34 minutes, isocratic hold at 25% B and 75% C for 1 minute, and a return to initial conditions of 100% solvent A over 4 minutes (a modification of Chen et al., 2001). Eluted pigments passed through a photo-diode array detector and ultraviolet-visible spectral characteristics were scanned between 350 and 750 nm. Quantification was based on scanning peak areas at 435 nm and calibrating to a set of commercial standards (DHI Denmark). Pigment concentrations are reported as molecular weights of pigments in nanomoles per unit organic matter of sediments.

3.5.1. Pigment affinities

Produced by algae, phototrophic bacteria and higher plants, chlorohyll and carotenoid pigments are useful to infer past phototrophic production and shifts in primary producer communities, providing essential information on lake trophic state. Pigments detected in the sediments from Lake Væng include fucoxanthin and diatoxanthin (from siliceous algae), alloxanthin (cryptophytes), chlorophyll *b* and lutein (chlorophyte algae and also higher plants including macrolimnophytes), aphanizophyll (filamentous cyanobacteria), zeaxanthin, canthaxanthin, echinenone (all cyanobacteria), chlorophyll *a* and β-carotene (all algae and higher plants), okenone (Chromatiales; the obligate anoxic microbes purple sulphur bacteria) and the ultraviolet radiation (UVR)-absorbing compound identified in Leavitt et al. (1997), which is often produced by cyanobacteria as a photo-protectant. An index of water clarity (the UVR index) was created by determining the amount of UVR pigment produced relative to quantity of algal pigments. Thus, the UVR index is estimated as UVR pigment divided by the sum of the most abundant pigments (alloxanthin + diatoxanthin + lutein-zeaxanthin) and multiplied by 100 (see Leavitt et al., 1997 for further details).

3.6. Numerical analyses

The continuous and semi-quantitative pigment concentration profiles were divided into zones using constrained optimal sum of squares partitioning available in the software package Zone v. 1.2 (Juggins 1991). We estimated the number of significant zones through comparison with a broken-stick model as described by Bennett (1996). All proxies were subsequently presented and discussed using this pigment-based division of the core data.

Pigment concentration assemblages were summarized using detrended correspondence analysis (DCA by segments, no transformation) to reflect overall changes in the major groups of algal primary producers. Such procedure helps to understand the ecological trajectory over time. While pigment gradient length was only 1.03 standard deviations, we chose DCA over PCA because it resulted in better separation in the sample plot. Remains of macrolimnophytes were too rare in the Lake Væng record to allow numerical analysis. We quantified ecological (pigment) change since pristine (pre-agricultural) conditions by first selecting the samples from 7000 to 6000 cal. yrs BP and then calculating the mean pigment assemblage of these 39 samples. Samples earlier than 7000 BP were left out in this calculation because catchment ecosystem adjustments following the Early Holocene warming were very slow (e.g., Giesecke et al., 2017), and such slow changes may have had cascading effects on lake status. In contrast, the period from 7000 to 6000 BP has been identified as ecologically less variable in terms of regional catchment vegetation (Odgaard, 1994). We compared all younger samples to this pre-agricultural baseline assemblage using chord distance as a dissimilarity measure. To do this, we converted the pigment data to percentage of all pigments (excluding the UV-index). Following linear detrending against time, the correlation of chord distance values with detrended Ti counts (a proxy for erosional input) was calculated for the period 6000-0 BP. All ordinations were performed using Canoco 4.5. Stratigraphic diagrams were plotted using the program C2 (Juggins, 2005) and edited in Adobe Illustrator.

4. Results and interpretations of proxy records

4.1. Sediments, ages and sedimentation rates

We recovered a 1780 cm long sediment succession from Lake Væng. The succession comprised glaciofluvial sand, a thin layer of clay, peat, carbonate-rich gyttja and fine-grained detritus gyttja (Fig. 2). The peat was ^{14}C-dated to *c.* 10 930 cal. yrs BP (Table S1). Gyttja started to accumulate about 9 400 cal. yrs BP, and the sedimentation rate during gyttja deposition was fairly constant at about 1.7 mm/year (Fig. 2). One sample, AAR-24965 (Table S1; Fig. 2) from a depth of 1078–1082 cm is considered an outlier, because it is younger than expected. Given the depth of the Early Holocene basin, and the lack of topographic gradient in the lake catchment, the lake likely formed as a result of the melting of buried stagnant ice (kettle hole lake). The fairly constant sedimentation rates at the central coring point may indicate sediment focusing in the centre of the lake during the earlier part of the record (steeper slopes), and an overall increase in lake-wide sedimentation, as the area of accumulation tends to increase over time in lake basins (Davis et al., 1984).

4.2. The titanium record

The titanium (Ti) record from Lake Væng is interpreted as an indicator for catchment erosion, as Ti has been shown as a useful proxy of clastic input and resulting nutrient flows to lakes (Kylander et al., 2011; Boyle et al., 2015; Davies et al., 2015). The record shows a low and fairly constant level until *c.* 5000 cal. yrs BP. Somewhat elevated contents of Ti are observed between *c.* 5000 and 3000 cal. yrs BP. Within this period, several small peaks are identified. From *c*. 3000 to *c*. 1250 cal. yrs. BP the average Ti level is similar to the previous period, but variability is much higher with pronounced peaks around *c*. 2700, 2300 and 1600 cal. yrs BP. (Figs 3-5). A distinct low level is seen around *c.* 1250 cal. yrs BP, which is followed by an abrupt and large increase peaking at *c.* 1000 cal. yrs BP, indicating a marked increase in catchment erosion. These high Ti contents are maintained until *c*. 500 years ago, when sediment Ti began to decline towards present-day values.

4.3. Lake and catchment biota

Figures 3-5 present detailed results of the macrofossil and pigment assemblage analyses, alongside results of the inorganic phosphorus (P) and LOI analyses, and the sediment Fe/Mn ratio. These proxy diagrams were divided into six zones (see 3.6. for methodology).

4.3.1. Zone 1 (c. 11 000 – 7370 cal. yrs BP)

Catchment vegetation

The five lowest peat samples are characterised by common wood fragments and remains of *Betula* sect. *Albae* (tree birch), *Pinus sylvestris*, *Populus tremula*, *Carex* sp. and *Phragmites* (rare). The peat is characterized by many wood fragments, suggesting that the site was probably overgrown by open woodland vegetation. The presence of *Carex* and *Phragmites* shows that the ground was waterlogged. *Betula* sect. *Albae* and *Pinus sylvestris* dominated the Early Holocene woodlands in Denmark (Iversen, 1973). *Betula* sect. *Albae* spread at the onset of the Holocene, whereas *Pinus* arrived somewhat later and in western Jutland it spread at about 10 500 cal. yrs BP (Odgaard, 1994).

The three upper samples of peat consisted almost entirely of stems of the bryophyte *Tomentypnum nitens*, which is well known as a peat forming species of alkaline mires (Dickson, 1973). In addition to *T. nitens*, remains of the bryophytes *Fontinalis antipyretica* and *Sphagnum* sp. were also recorded, as well as remains of the trees *Betula* sect. *Albae*, *Pinus sylvestris* and *Populus tremula*, which were common in the region in the Early Holocene (Odgaard, 1994). The moss peat indicates that the site became wetter, perhaps due to melting of buried stagnant ice below the peat. The sediment probably accumulated in a small moss-rich mire surrounded by open woodland.

Since core material is not available to show the transition from peat to lake gyttja, we do not know if the transition from mire to lake was abrupt or gradual. The common presence of *Betula* sect. *Albae* and *Pinus sylvestris* may indicate that the coring site was close to the palaeo-shore, and that the lake at that time was relatively small. The first record of *Alnus glutinosa* is at 9200 cal. yrs BP, which is in accordance with studies of other Danish locations (Aaby, 1993; Odgaard, 1994), although some marine sites show older ages of macrofossils [Storebælt *c.* 9500 cal. yrs BP (Bennike et al., 2004), Aarhus Bay *c.* 9800 cal. years BP (Rasmussen et al., 2020)]. *Sphagnum* sp. remains are abundant between 9000 and 8500 cal. yrs BP, after which they nearly disappear from the record and reappear at greater numbers again in Zones 5 and 6. These remains indicate that swampy conditions were found along the shores of the lake.

Pinus disappears from the record around 8000 cal. yrs BP and *Betula* becomes rare. The tree macrofossil record is thereafter characterised by *Alnus glutinosa*. The decline in *Pinus* and *Betula* probably reflects that the forests around the lake were replaced by closed temperate deciduous forests. Regional pollen diagrams show that the forests were dense and dominated by broad-leaved deciduous trees such as *Corylus*, *Tilia*, *Quercus* and *Ulmus* (Iversen, 1973; Odgaard, 1994). The general lack of macrofossils of these species is a common feature of macrofossil studies of lake sediments (Watts, 1978).

Lake macrophyte, invertebrate and fish communities

Remains of lake macrophytes are rare and largely confined to *Najas marina*, *Nymphaea alba* and *Nuphar* sp. The scarcity of submerged macrophytes, particularly before 8000 cal. yrs BP, could be due to brownification, limiting light availability at the lake floor. This interpretation is in line with the low values of the pigment-based UVR-index (Fig. 5; low values indicate turbid/coloured water, high values clear water) and inferred swampy conditions along the shores of the lake.

The presence of the thermophilous plants *Najas marina* and *Cladium mariscus* in the early part of the record indicates that summer temperatures around 9000 – 8000 cal. yrs BP were at least similar to present temperatures. *Najas marina* is a submerged macrophyte that grows in brackish water or carbonate-rich fresh water with high conductivity (Bennike et al., 2001), whereas *Cladium mariscus* is a calciphilous reed plant that was common and widespread in eastern Denmark in the Early Holocene. While *Najas marina* survived in many Danish lakes until recently, *Cladium mariscus* declined due to leaching of the calcareous soils throughout the Holocene and due to decreasing temperatures after the Holocene thermal maximum. Only a few studies have previously found *Cladium mariscus* macrofossils from Holocene deposits in Jutland (Jonassen, 1950).

The most abundant remains of fresh water animals include ephippia of *Daphnia pulex* and statoblasts of the bryozoan *Cristatella mucedo*. Remains of ostracods and gastropods are rare. The high abundance of *Daphnia pulex* ephippia indicates that the predation pressure by fish was limited before *c.* 9000 cal. yrs BP (Davidson et al., 2010). *Perca fluviatilis* (perch) remains are found throughout the zone, but their abundance is low compared to following zones.

Algal communities, nutrients and primary production

The pigment data (β-carotene) indicate relatively low algal production throughout the first *c.* 5000 years of Lake Væng. The loss-on-ignition (LOI) record representing the organic matter content of the sediments agrees with this observation, as values are clearly lowest in this zone (starting below 10% and stabilising at *c.* 20% around 8000 cal. yrs BP). The inorganic P profile largely mirrors LOI, showing lowest values prior to Zone 4 at the bottom of the core (*c.* 3.6 mg/g). As a large part of the HCl-extracted inorganic P is in the form of calcium phosphates (see methods), the slowly increasing trend in Zone 1 (and into Zone 2) is likely due to natural leaching of Ca from the catchment soils.

All primary producer groups found in the sediment record are represented in this zone (Fig. 5), apart from purple sulphur bacteria (okenone). Especially cyanobacteria, however, but also siliceous algae occur at clearly lower concentrations compared to the following zones. The absence of the UVR-screening pigment in Zone 1, the scarcity of macrolimnophytes, and evidence of *Sphagnum*-rich vegetation surrounding the basin indicate that the water was stained brown by humic substances. Such colouring may have limited primary production through light limitation, as is common in dystrophic waters. Around *c.* 8000 cal. yrs BP, low levels of the UVR index are observed. These low levels could indicate improving water clarity in the lake in concert with the decline in swampy *Sphagnum*-rich vegetation, as algae produce sunscreen compounds when exposed to UVR light (Leavitt et al., 1997). Water level fluctuations can also account for them, when marginal habitats (which have higher UVR exposure) are colonized by cyanobacteria, which produce UVR-protective compounds as protection from periodic UVR exposure (Cantonati et al., 2014).

4.3.2. Zone 2 (7370–6050 cal. yrs BP)

Catchment vegetation

Alnus glutinosa and *Populus tremula* characterize the tree macrofossil record in this zone. The decline in *Pinus* and *Betula* in the previous zone likely reflects the spread of closed temperate deciduous forests (as documented by local and regional pollen diagrams, e.g. Odgaard 1994), which then dominated during this zone.

Lake macrophyte, invertebrate and fish communities

Macrophyte findings are also in this zone largely confined to *Najas marina*, *Nymphaea alba* and *Nuphar* sp. The submerged *Najas marina* shows a continuous presence from c. 6500 cal. yrs BP until ca. 4500 cal. yrs BP and *Chara* sp., a genus consisting of likewise submerged water plant species appears in the record at the same time. *Perca fluviatilis* remains are most abundant in the whole sediment record during the Holocene thermal maximum (between 8000 and 5000 cal. yrs BP), when the lake was at its clearest based on the UVR-index (Fig. 5).

Algal communities, nutrients and primary production

We observe increased concentrations of pigments belonging to siliceous algae (diatoms and chrysophytes), cryptophytes, chlorophytes and cyanobacteria. These concentrations indicate increased production in these groups as light availability increased, while the overall algal production was still relatively low (β-carotene). Within the whole sediment record, the UVR index is highest in this zone and in the beginning of Zone 3. The steady increase of inorganic P stabilises around 7.5 mg/g in the end of this zone, until ca. 4500 cal. yrs BP.

4.3.3. Zone 3 (6050–2700 cal. yrs BP)

Catchment vegetation

The land plant record is characterised by the dominance of *Alnus glutinosa*, which probably grew along the margin of the lake and in areas with wet soil. *Betula* sect. *Albae* remains are rare but occur through the zone, whereas *Populus tremula* remains disappear around 3700 cal. yrs BP. Other woody plants are represented by a few remains of *Sorbus aucuparia* and *Prunus padus*. Remains of wetland plants are rare. Regional pollen diagrams show some disturbance, especially by animal husbandry, meaning that the forests during this period became more open and *Betula* and *Corylus* increased, whereas *Tilia*, *Fraxinus* and *Ulmus* decreased (Iversen, 1973; Odgaard, 1994).

Lake macrophyte, invertebrate and fish communities

Water plants are only present in low numbers. Remains of *Najas marina* show a continuous record and highest abundances during the first half of the zone, simultaneously with the only near-continuous occurrence of *Chara* sp., before disappearing entirely from the sediment record around 4500 cal. yrs BP. The most abundant water animal remains in this zone are statoblasts of the bryozoan *Plumatella* sp. (mainly *Plumatella repens*, especially around 4000–3000 cal. yrs BP) and the ostracod *Cyclocypris laevis* (in the middle of the zone). Other ostracods are rare. Freshwater snails (*Valvata* spp.) and freshwater bivalves (*Pisidium* sp.) disappear from the sediment record by the middle of this zone (around 4000 cal. yrs BP). Egg cocoons of the fish leech *Piscicola geometra* first appear in this zone and display a near-continuous record (albeit with low abundances) to the top of the core. The fish fauna includes *Scardinius erythrophthalmus* (common rudd), which first appears in this zone, and *Perca fluviatilis*, which shows a decline in the abundance of remains compared to the previous zone.

The continuous presence of *Najas marina* in Lake Væng during the Mid-Holocene may reflect peak summer temperatures during this time. It survived in many Danish lakes until recently, however, and may have disappeared rather recently from Lake Væng because the water became more eutrophic and turbid, as documented by Anderson and Odgaard (1994). The pigment data (UVR-index) indicate greatest water clarity at the same time as the continuous *N. marina* occurrence, which lends further support to the reasoning outlined above on its disappearance. While favourable light conditions for submerged macrophytes may also occur during lower lake levels, palaeohydrological data from Lake Bliden on Zealand, Denmark indicate that the Holocene thermal optimum was wet, becoming drier towards its end around 5700 cal. yrs BP (Olsen et al., 2010). Regional lake level reconstructions from southern Sweden indicate lower lake levels in the Early

Holocene and again around 5600–5400 cal. yrs BP (Gaillard and Digerfeldt, 1991). Thus, these studies do not support lake level lowering during the presence of photo-protectant pigments and *N. marina* in the Lake Væng record.

With infilling of the lake, the littoral zone expands and (submerged) macrophyte cover would be expected to increase. In the Lake Væng record, however, we witness the opposite, i.e. increasingly sparser macrophyte cover towards the present times, which would indicate increased lake turbidity, in line with the decrease in the UVR-index (see below). The decline in *Perca fluviatilis* and increase in *Scardinius erythrophthalmus* remains could indicate a change in the fish community towards dominance of planktivorous cyprinid fish, commonly observed in eutrophied lakes (Sandström and Karås, 2002). *Plumatella* species have likewise been found to benefit from higher nutrient concentrations (Hartikainen et al., 2009).

Studies have found positive correlations between the frequency of fish leech (*Piscicola*) and both submerged macrophyte and fish abundance (Odgaard and Rasmussen, 2001; Sayer et al., 2016). Although rare throughout the core, macrophyte and fish remains are even rarer in the section of the core (from *c.* 4500 cal. yrs BP to the top), when *Piscicola* is present. On the other hand, *Scardinius* remains appear around the same time as *Piscicola*, possibly indicating an increase in cyprinid fish.

Algal communities, nutrients and primary production

Several simultaneous changes are observable around 4500 cal. yrs BP. Concentrations of β-carotene (reflecting total algal production) show a *c.* 4-fold increase compared to the very low concentrations of the previous zones. Both LOI and inorganic P increase to *c.* 30% and *c.* 10 mg/g, respectively. The UVR index decreases clearly, and we observe the initial change towards higher Fe/Mn values. Concentrations of diatoxanthin, which is produced by diatoms, increase towards the upper part of this zone. After *c.* 3500 cal. yrs BP, okenone from purple sulphur bacteria appears for the first time.

The increases in pigment concentrations and LOI indicate that the lake became more productive. The simultaneous increases in inorganic P and Ti (erosion) imply increased nutrient (P) inputs from the catchment. The observed decrease in the UVR-index indicates lower water clarity, which could be translated into increased turbidity due to higher algal production. By this time, the lake had likely become shallower due to infilling (Fig. 2), but it was probably still stratified, at least in the deeper parts of the lake. Infilling leads to expanded benthic and epiphytic areas for algal colonisation, which could also have increased sedimentary pigment concentrations. The onset of the presence of okenone in tandem with the first increase in the Fe/Mn ratio indicates development of anoxic habitats in the lake, which may derive from the decomposition of aquatic vegetation or planktonic seston. The decomposition leads to pockets of anoxic habitat in benthic areas, or (in stratified lakes) hypolimnetic anoxia during lake stratification.

4.3.4. Zone 4 (2700–1270 cal. yrs BP)

Catchment vegetation

Alnus glutinosa continues to dominate the land plant record. *Betula* sect. *Albae* is rare and nearly disappears at the transition between this zone and the uppermost two zones. Apart from one finding of *Sorbus aucuparia*, no other woody plant remains are recorded and wetland plant remains are very rare. Regional pollen studies from Jutland indicate that during the early part of this zone a reduction in woodland caused by extensive domestic grazing was prevalent. In the late part of the period (from about 1800 BP), a general relaxation of grazing pressure resulted in a reforestation during which *Fagus* spread in the forests (Iversen, 1973; Odgaard, 1994; Rasmussen, 2005).

Lake macrophyte, invertebrate and fish communities

Water plant remains are present in very low numbers. *Stratiotes aloides* appears for the first time in this zone. This species is commonly found at sheltered sites in eutrophic lakes (Hämet-Ahti et al., 1998). Its presence is noteworthy, because this plant is rarely recorded in Holocene lake sediments from Denmark (Bennike and Hoek, 1999), but its leaf spines are common in subsurface sediments of recently eutrophied shallow lakes (Odgaard and Rasmussen, 2001). *Stratiotes aloides* has been reported to show allelopathic suppression of phytoplankton growth in laboratory experiments (Mulderij et al., 2005), but any such effect is not detectable in our data (see algal discussion below). The bryozoan *Fredericella* sp. first appears around 2000 cal. yrs BP and its remains are relatively abundant from here to the top of the core. The bryozoan *Plumatella* sp. (mainly *Plumatella repens*) is near absent in the first half of this zone, but the abundance of its remains increases clearly at the same time with *Fredericella* before declining to rare occurrences at the end of the zone. *Perca fluviatilis* remains continue to decline towards the top of the core and are near absent in this zone. One occurrence of *Scardinius erythrophthalmus* is recorded.

The water plants and animals observed in this zone each indicate eutrophic conditions. Bryozoan adundance (*Fredericella* and *Plumatella*) is known to increase with higher nutrient concentrations, especially with increases in phosphorus (Hartikainen et al., 2009).

Algal communities, nutrients and primary production

The pigment record becomes more variable with oscillations in concentrations of most pigments and a pronounced assemblage readjustment where pigments from cyanobacteria (including filamentous cyanobacteria) become more dominant relative to siliceous, cryptophyte, and chlorophyte algal pigments (Fig. 5). LOI increases clearly in this zone, with highest values around 40% while, similar to the pigments, variability in inorganic P increases to display the highest values in the whole sediment record (1.94 mg/g) at *c.* 2100 cal. yrs BP, around the same time with a marked increase in Fe/Mn. Okenone increases abruptly at *c.* 1700 cal. yrs BP. The increase in pigment concentrations and LOI, and the shift towards cyanobacteria, which are strongly associated with nutrient enrichment (Taranu et al., 2015) each indicate that the lake became more productive compared to the previous zone, while lake bottom anoxia also increased (indicated by okenone and Fe/Mn). Increases in bottom water anoxia are commonly associated with eutrophication in stratified lakes as the supply and subsequent decomposition of organic matter to the lake bottom waters leads to oxygen drawdown (Lami et al., 1994; Maheaux et al., 2016). Shallow lake sediments may also be anoxic, however, despite overlying well-aerated water. Their well-oxidized sediment surface does not preclude the potential release of mobile P to the overlying water column (Tammeorg et al., 2020). Based on the inorganic P profile of Lake Væng, it was mobilised from the sediment into the water column, further increasing eutrophication.

4.3.5. Zone 5 (c. 1270–250 cal. yrs BP)

Catchment vegetation

Land plant remains in this zone are dominated by *Sphagnum* sp. and *Juncus* sp. Remains of woody plants are rare and confined to *Betula* sect. *Albae* and *Alnus glutinosa*, which occur in the lower part of the zone. Regional pollen diagrams show that the landscape became progressively more open due to expanding pastures and eventually also arable fields (Iversen, 1973; Odgaard, 1994; Rasmussen, 2005). The *Sphagnum* and *Juncus* remains indicate that boggy vegetation was reappearing along the shores of the lake. Similar expansions of *Sphagnum* in the Late Holocene are also seen at other sites in Jutland (Odgaard, 1994) and may indicate acidification of soils around the lake.

Lake macrophyte, invertebrate and fish communities

Macrolimnophytes are very rare, represented by a few findings of the floating-leaved *Nymphaea alba* and a single oospore of the submerged macrolimnophyte *Chara* sp. Water animals are represented by cocoons of the leaches *Piscicola geometra* and *Erpobdella* sp., larval cases of the caddis fly *Orthotrichia* sp. and statoblasts of the bryozoans *Cristatella mucedo*, *Plumatella* sp., and *Fredericella* sp. The former are all rare, while *Fredericella* sp., which thrives in eutrophic conditions, dominates this zone.

Algal communities, nutrients and primary production

Maximum pigment concentrations occur during this zone, with particularly elevated concentrations of planktonic filamentous cyanobacteria pigments (despite the by now shallow lake depth, see Fig. 2). LOI largely mirrors total algal production (β-carotene), showing highest (albeit variable) values in the whole sediment record of up to *c.* 50%. Okenone concentrations are also highest in the whole sediment record at the beginning of the zone, before declining and disappearing entirely around 500 cal. yrs BP, largely mirrored by Fe/Mn. Maximum algal and filamentous cyanobacterial abundance indicate very productive conditions. Inorganic P values clearly decrease compared to the previous two zones, likely reflecting that a large proportion of the inorganic P is mobilized into the water column (Anderson et al., 1993 and references therein).

Based on the proxy records, the time period from 1250 to *c.* 250 cal. yrs BP was the most eutrophic (likely hypertrophic) period in the history of Lake Væng. Increases in okenone are regularly associated with eutrophication in stratified lakes (Guilizzoni and Lami, 1992), but okenone declined in Lake Væng during this highly productive phase. An increase in lake turbidity from higher phytoplankton production might have reduced light penetration to the deeper waters, eliminating the habitat for photosynthetic bacteria. Catchment deforestation, however, likely increased wind fetch and lake mixing (Lotter, 2001; Romero et al., 2006) which, in combination with progressive shallowing of the lake following sediment infilling, will have decreased stable deep-water habitats for anaerobic phototrophs.

4.3.6. Zone 6 (ca. 250 cal. yrs BP – present)

Catchment vegetation

Apart from rare *Betula* sect. Albae, *Juncus* sp. and *Sphagnum* sp., which shows a steady decline throughout the zone, no other land plant remains are found. At present, the area close to the lake is forested, but according to historical records these are some decades old coniferous plantations.

Lake macrophyte, invertebrate and fish communities

In this uppermost zone, the sediment record is devoid of remains of macrolimnophytes. All water animal remains are rare, apart from *Fredericella* sp., and remains of both leaches and fish disappear in the top of the core.

Algal communities, nutrients and primary production

During the last c. 250 years of our record, concentrations of β-carotene decrease markedly, while concentrations of chlorophyll a show a slight increase. LOI follows the notable trend in β-carotene and decreases from c. 50% to c. 25%. Among the different algal groups, cyanobacterial pigments decline clearly, but siliceous algal, cryptophyte and chlorophyte pigments mostly increase towards the top of the sediment record. At the same time the UVR index increases markedly. These shifts in algal communities, decline in LOI, increase in the UVR-index, complete absence of okenone and clear decrease in Fe/Mn indicate a moderate recovery towards a less-enriched lake ecosystem and decreased turbidity of the shallow waters (light penetration to the lake bottom). This is in line with the reduced catchment input represented by declining Ti-levels. However, there is no indication of a recovery of submerged macrophyte vegetation.

4.4. Numerical analyses

The DCA of the pigment assemblages clearly shows a limited amount of change before *c.* 6000 cal. yrs BP, after which the differences among samples increased as the trajectory of ecological change became more dynamic with increased catchment inputs (Fig. 6A). The assemblages of Zone 5 deviate markedly from the rest of the core. Interestingly, the two modern samples (last 50 years) show a clear trend back towards assemblages that are more similar to pristine conditions.

The pigment chord distance results reflect a long period until about 2500 cal. yrs BP with relatively little change compared to the baseline, albeit with some distinct spikes (Fig. 6B). This initial change was followed by much more different assemblages from *c.* 1250 cal. yrs BP onwards before finally returning to more similar biotic assemblages over the last century. A strong correlation between Ti and pigment change (Fig. 6B, $R^2 = 0.37^{***}$ based on detrended values) indicates that the changes in primary producers in the lake are directly correlated with inputs of allochthonous minerals via processes such as soil erosion and shifts in land drainage.

5. Discussion

The lack of Late Glacial organic sediments and the presence of Early Holocene peat in the bottom of the Lake Væng record show that the lake did not form until the Early Holocene, about 9400 cal. yrs BP. The lake probably formed by melting of a body of stagnant glacier ice and the lack of Late Glacial and earliest Holocene sediments (11,700 to 9400 cal. yrs BP) indicates that stagnant glacier ice persisted until several millennia unto the Holocene. The presence of *Cladium mariscus* in the record indicates summer temperatures similar to the present at *c.* 8500 cal. yrs BP. The oldest dated Holocene finds of *Cladium* fruits from Denmark, however, gave an age of *c.* 11 000 cal. yrs BP (Bennike and Jensen, 2011), indicating rapid warming soon after the beginning of the Holocene at 11 700 cal. yrs BP.

Iversen (1973) concluded that the mean July temperature was 2–3°C higher than at present during the Holocene thermal maximum, in good accordance with more recent estimates based on pollen data (Brown et al., 2011). The forests in the catchment of Lake Væng changed from pine dominance until around 8000 cal. yrs BP to a closed temperate deciduous forests dominated by broad-leaved species such as *Corylus*, *Tilia*, *Quercus* and *Ulmus* (Iversen, 1973; Odgaard, 1994), which was gradually changed to secondary ecosystems by early agriculture during the Neolithic (5900–3600 cal. yrs BP) (Iversen, 1973).

The landscape

Titanium is considered a reliable indicator of terrigenous catchment inputs (Kylander et al., 2011; Boyle et al., 2015; Davies et al., 2015). Hence the Ti record from Lake Væng is interpreted as a proxy of soil erosion, which was mainly controlled by the ratio of open to forested land. Generally, lack of forest reduced the landscape resistance to erosion. In open landscapes, runoff energy is also elevated. During prehistory, the degree of open land depended especially on the intensity of grazing by domestic life stock and later by clearance for arable farming (Fig 7). Terrestrial erosion tends to peak just after deforestations begin, and soils which were previously protected by forests became exposed. In contrast, erosion relaxes to lower levels when the easily eroded sediments gradually become depleted (Prosser and Williams, 1998). This means that sedimentary Ti cannot be expected to be a direct proxy of landscape openness, but rather a reflection of the availability of exposures of erodible catchment sediments. Erosion peaks can be expected to reflect deforestation events while extended high erosion rates may represent continuously declining forest cover or permanent crop cultivation. Lower erosion levels reflect landscapes resistant to erosion, either because they are relatively densely forested, or because they are mature in the sense that erodible sediments have already been flushed off.

The erosion record of Lake Væng is interpretable by reference to existing local pollen records, such as from Ilsø (14 km east, Søe et al., 2017), Taastrup Sø (20 km northeast, Søe et al., 2017) and Dallerup Sø (30 km southeast, Nielsen & Odgaard, 2010). When interpreting Ti as an erosion proxy for land use history in Denmark (Fig. 7), it is clear that, before the introduction of agriculture (the Mesolithic period until 5900 cal. yrs BP), erosion in the Lake Væng catchment was low and fairly constant. This is in accordance with local pollen records, reflecting dense deciduous woodlands in the area. The first clearly observable increase in erosion at Lake Væng is seen in the Middle Neolithic B (Single Grave Culture, 4400–4800 cal. yrs BP), a period known from several nearby pollen records to show extensive landscape opening in western and Central Jutland, caused by animal husbandry (Odgaard, 1994; Søe et al., 2017). After a relaxation reflected in the pollen records as reforestation, erosional inputs indicate that the intensity of landscape disturbance grew again through the Late Neolithic and Early Bronze Age, a period of expansion of cultural grasslands (Søe et al., 2017). During the Late Bronze Age and the Pre-Roman Iron Age, erosional inputs at Lake Væng peak, which is in accordance with local palynological records showing a pronounced transition to mostly very open pastoral landscapes during these periods (Odgaard and Rasmussen, 2000; Søe et al., 2017). Pollen records indicate that these open landscapes generally persisted in the region through the Roman Iron Age (Nielsen and Odgaard, 2010), and the lower Ti counts here probably reflect the maturity of the pastoral landscape. A conspicuous peak is observed at the transition to the Germanic Iron Age, which otherwise shows low values in accordance with palynological results indicating reforestation in many areas of Denmark as well as locally (Nielsen and Odgaard, 2010; Søe et al., 2017). This peak is followed by an abrupt and very large increase in catchment inputs at the transition to the Viking Age, which defined a period of strong deforestation (Nielsen & Odgaard, 2010; Søe et al., 2017). While erosional inputs at Lake Væng decrease somewhat in the Medieval Period, overall high levels of catchment disturbance persisted until around 200 cal. yrs BP, reflecting a period with strong increases in arable farming well documented by local pollen records. During the most recent century, partial afforestation of the area around Lake Væng will have played a role in reducing landscape erosion. Overall, the very strong correspondence between erosional peaks and local pollen records showing transitions to periods with expansion of cultural grasslands or cropland evidences the strong importance of land use for catchment erosion at Lake Væng. Since documented Mid-/Late Holocene climate changes in the area are minor, possible direct effect of climatic variation on the erosion pattern of Lake Væng was likely subtle in relation to the large impacts from land-use changes. We have not identified exclusive climate signals in the erosional record.

Comparing the Lake Væng Ti-record with other records of catchment sediment yields from Denmark reveals clear similarities (Fig. 7). While Lake Væng shows the earliest signs of catchment erosion linked to human disturbance of the landscape during the Middle Neolithic, all records indicate increased and prolonged deforestation events in the catchment during the Late Bronze Age and/or Pre-Roman Iron Age (in some cases also evident during the Roman Iron Age). This increase suggests that, overall, the early phase of agriculture in Denmark during the Early Neolithic had relatively little effect on landscape openness and soil erosion, and more pronounced deforestation only took place in the Bronze and Iron Ages. Areas with strong activity by the Single Grave Culture, however, such as at Lake Væng, reflect elevated erosion already in the Middle Neolithic. The marked minimum in erosion during the Germanic Iron Age is also a common feature, probably related to reforestation caused by social unrest or economic depression and associated changes in landscape management during the Migration Period.

The most conspicuous common feature in the records is the strong increase in soil erosion at the beginning of and during the past millennium. This development reflects the large-scale deforestation documented by pollen records and resulted in a landscape dominated by pastures and agricultural fields (Odgaard and Rasmussen, 2000; Søe et al., 2017). These data further reveal marked landscape disturbance continuing into modern times until a more recent decrease over the last few hundred years (apart from Gudme Sø). A similar large increase in terrigenous inputs during the Medieval Period has also been observed in other European lake records (Bork and Lang, 2003; Boyle et al., 2015; Bajard et al., 2016). The timing of this marked landscape change coincides with the introduction of the heavy mouldboard plough in Northern Europe. This plough could turn over the heavy, fatty and moist clay soils of the region and plough manure into them, markedly increasing yields and transforming European agriculture and economies (Andersen et al., 2016). The decreasing trend in erosion of the most recent century may reflect two developments: 1) increasing afforestation in Denmark resulting in a development in forest cover from 4% in AD 1805 (Fritzbøger, 1992) to 14.6 % in 2018 (Nord-Larsen et al., 2020) and 2) the reduction in livestock during the same period (Dalgaard et al., 2009), which reduced grazing at lake shores and accordingly led to denser marginal vegetation of streams and lakes with a more effective filtering of surface overflow.

The exceptionally long continuous erosion record from Fuglsø includes early catchment inputs that have a natural origin. It begins with a large Ti-peak related to the transition from minerogenic lake sediments to gyttja. The following Early Holocene peaks are probably due to short cooling events, such as the Erdalen Event 1 (Nesje, 2009) and the 8.2 event (Alley et al., 1997) intermittently resulting in vegetation types less resistant to erosion.

The lake

The most striking change in the Lake Væng ecosystem is recorded by the chord distance dissimilarity increase at about 1200 cal. yrs BP and also clearly evident from zones 5 and 6 samples in the DCA plot (Fig. 6). This change occurs concurrent with the most marked increase in Ti counts (Figs 6, 7). The lake most likely became hypertrophic, with high production of planktonic algae, blooms of filamentous cyanobacteria, and sediment anoxia (Fig. 5). Blooms of filamentous cyanobacteria are commonly associated with eutrophication, particularly increases in phosphorus, which would have been supplied by both increased catchment nutrient inputs and internal loading from anoxic sediments (Taranu et al., 2015; McGowan, 2016). This indicates that Viking Age/Medieval land disturbances and farming practices led to major increases in nutrient loading to the lake and increased the prevalence of these nuisance and potentially toxic taxa. The evidence from this study signifies that the local introduction of the heavy mouldboard plough changed Lake Væng far beyond previous ecosystem conditions, and also conditions prevailing in the 21st century. At Dallund Sø, where one of the few existing detailed multiproxy studies on landscape-lake linkages over the past millennia was conducted, diatom-inferred TP concentrations increased markedly from *c.* 30 µg/L to > 200 µg/L at the beginning of the Medieval Period, resulting in large changes in lake productivity in concert with enhanced catchment inputs (Fig. 7C; Bradshaw et al., 2005).

Interestingly, Lake Væng began to recover after the period of intense soil erosion in the Viking Age/Medieval Period towards prior pigment assemblages, and water clarity began to increase (Fig. 5). This recovery indicates that the marked disturbance may have led to greater degradation in water quality relative to more recent times, when Danish lakes are well-known for having water quality problems (Jeppesen et al., 2000). Despite the increase in water clarity and decreased catchment inputs, the submerged macrophyte vegetation has not recovered (Fig. 3). Recent biomanipulation projects have had only temporary success in restoring submerged vegetation (Søndergaard et al., 2017).

Notably, evidence also exists of prehistoric disturbances at Lake Væng as early as in the Middle Neolithic *c.* 4500 years ago, which predates the oldest reported record of aquatic changes caused by human activity in Denmark (Dubois et al., 2017). With the first increases in erosional inputs to the lake, it became more turbid, as evidenced by the decline of the UVR-index, and primary production increased from the background level of the previous almost 5000 years (first clear increase in β-carotene). The increase in turbidity apparently affected the submerged macrophyte vegetation adversely (seen as the decline of *Najas marina*), and possibly changed the dominant fish towards cyprinid species (Figs 3, 4). Bryozoans indicating elevated nutrient levels also become common from here on. From the beginning of the Late Bronze Age (*c.* 3000 cal. BP) onwards, cyanobacterial production increased, including filamentous cyanobacteria, and the first signs of anoxia appear (increase in okenone and Fe/Mn), which are likely associated with more intense decomposition of organic matter (Maheaux et al., 2016). In contrast, at Dallund Sø, clear indications of ecosystem changes dated later towards the end of the Late Bronze Age (Bradshaw et al., 2005).

In Denmark, intense landscape modifications inferred from sedimentary pollen started during the mainly pastoral Single Grave culture (4800-4400 cal. yrs BP), but with a strong regional bias towards landscapes to the west and north of the East Jutland stationary line of the last glaciation. As an example, strong deforestations during this period caused by intense animal husbandry are characteristic of northwestern areas and some parts of Central Jutland (Andersen, 1993; Odgaard, 1994). Landscape modification east of this line (this study; Bradshaw et al., 2005) was apparently less intense in Denmark before the Late Bronze Age (Fig. 7), after which clearly detectable influences on lake ecosystems are evident. With the extensive deforestation and new agricultural practices in early historical time (such as the heavy mouldboard plow), these lakes responded with a regime shift (Scheffer and Jeppesen, 2007). While lake-ecosystem response is always dependent on regional and local factors including topography, soils, hydrology and climate, it is plausible — based on existing evidence on modification of the European landscape since the Neolithic (summarised in Dubois et al., 2017) – that a notable number of European lowland lakes may have first shifted into a degraded ecological state already many centuries ago, especially about 1200 cal. yrs BP, and possibly followed a recovery pathway, before again responding to increasing pressures that the modern society poses on lakes (Jenny et al., 2016; Haas et al., 2019). Hence, considering pre-industrial conditions as relatively pristine (and hence suitable as reference levels for recent eutrophication) is not necessarily a valid assumption in landscapes that have been intensively used by humans over the past millennia. These findings corroborate the conclusion of Bradshaw et al. (2006), who found high P concentrations in a number of Danish lakes as early as AD 1800.

Finally, it is noteworthy that cyanobacteria have been consistently present in Lake Væng throughout the Holocene, albeit at mostly lower abundances. This may be connected with the lake's supply of groundwater with high phosphorus concentrations. Such naturally elevated abundances of cyanobacteria have been recorded from other lakes in moraine landscapes where groundwater supply dominates (McGowan et al., 1999). Debate still exists about the relative roles of groundwater supply and internal recycling of P in lakes (Kilinc and Moss, 2002; Nisbeth, 2019a,b). In the case of Lake Væng, the amount of groundwater entering the lake and the groundwater-delivered DIP have not changed significantly over recent time (Kazmierczak, 2020), and changes in algal abundances are tightly coupled to erosional inputs (based on pigment chord distance analysis, Fig. 6B). Hence the observed increases in cyanobacterial blooms and primary production are most likely a result of catchment disturbance due to early human activity.

6. Conclusions

The results based on the multi-proxy study of the Lake Væng sediments show that the record begins with peat, and the lake probably formed by melting of buried stagnant glacier ice in the Early Holocene. Forests in the catchment of Lake Væng changed from pine and birch dominance prior *c.* 8000 cal. yrs BP to closed temperate deciduous forests dominated by broad-leaved species, which remained in the pristine landscape until the first human disturbance.

Following up the specific research questions in the Introduction (section 1.): 1) The first signs of clearances of these primeval forests around the lake are seen in the Middle Neolithic at *c.*

4500 cal. yrs BP. Erosional inputs to the lake were relatively low, however, indicating that the region was still dominated by dense deciduous forests. It is obvious from the archaeological record that farming had started, but the local impact on the landscape was limited, presumably because the human population was small (Gron and Rowley-Conwy, 2017). Despite the limited nature of the impact, the lake still responded by becoming more turbid and nutrient rich, with clear negative impacts on the submerged aquatic plants, possible changes in the dominance of fish species and shifts towards more eutrophic invertebrate species. 2) Larger peaks in erosional inputs are seen in the Late Bronze Age and Pre-Roman Iron Age, with clear lake responses including smaller blooms of filamentous cyanobacteria and first signs of anoxia. A very strong erosional signal at about 1200 cal. yrs BP may be related to the introduction of the mouldboard plough. At this time the lake responded with a regime shift. It became hypertrophic and very turbid, with high production of potentially bloom-forming filamentous cyanobacteria, and bottom-water anoxia. 3) The human impact in the Medieval Period led to especially severe degradation in water quality and a more degraded ecosystem state compared to recent times. 4) Lake response is near-contemporaneous with catchment inputs and the response is proportional, i.e. with greater sediment and nutrient loading we observe progressively more marked deterioration of the lake ecosystem.

As several Danish and European lake records on catchment disturbances share similar features to the record from Lake Væng , it is possible that a number of lowland European lakes experienced poor water quality already millennia ago, and certainly at the time of extensive forest clearances and new agricultural practices about 1200 cal. yrs BP.

Appendix A. Supplementary data

Supplementary material related to this article can be found in the online version, at xxx

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Figure captions

Fig. 1. A. Map of Denmark showing the location of Lake Væng (VS) discussed in this study. AB: Aarhus Bay, DS: Dallund Sø, LB: Lillebælt, SB: Storebælt. **B.** Google Earth satellite image of Lake Væng. The dot shows the core position. **C.** Historical map, ca. 100 years old.

Fig. 2. A. Simplified log for the Lake Væng sediment record. **B.** Age–depth model for the succession from Lake Væng. The depth of the lowermost sample is uncertain. One sample is considered an outlier.

Fig. 3. Simplified macrofossil concentration diagram for Lake Væng (terrestrial, wetland and limnic plants). Radiocarbon ages are shown on the left of the diagram. Zone boundaries (based on pigment data) are shown with horizontal dashed lines and the zones are numbered on the right of the diagram.

Fig. 4. Simplified macrofossil concentration diagram for Lake Væng (invertebrate and vertebrate remains). Radiocarbon ages are shown on the left of the diagram. Zone boundaries (based on pigment data) are shown with horizontal dashed lines and the zones are numbered on the right of the diagram.

Fig. 5. Sedimentary pigment stratigraphy, LOI, inorganic (HCl-extracted) phosphorus, Fe/Mn ratio and titanium records from the Lake Væng sediment core. Affinities of pigments with particular algal groups are indicated in the headers and calibrated radiocarbon ages are given on the left of the diagram. The UVR index indicates water clarity and is calculated as indicated in the methods section. Zone boundaries are shown with horizontal lines and zone numbers are shown on the right of the diagram.

Fig. 6. A. Detrended correspondence analysis (DCA) of pigment data with colour coding according to the zonation used in the paper. The ages of the two youngest samples are shown in years (Common Era). **B.** Ti counts (erosion proxy) and pigment chord distance values (perturbation proxy) for the last 6000 years plotted against age.

Fig. 7. Records of soil erosion from Lake Væng compared with other erosion records from Denmark. **A.** Lake Væng, this study; raw titanium counts per second), **B.** Fuglsø in eastern Jutland (Odgaard et al., 2017; normalized titanium counts), **C.** Dallund Sø on northern Funen (Rasmussen and Bradshaw, 2005; minerogenic matter), **D.** Gudme Sø on south-eastern Funen (Rasmussen and Olsen, 2009; sediment accumulation rate of minerogenic matter), **E.** Ilsø in eastern Jutland (Søe et al., 2017; titanium counts per second). The inset map shows the location of the sites.

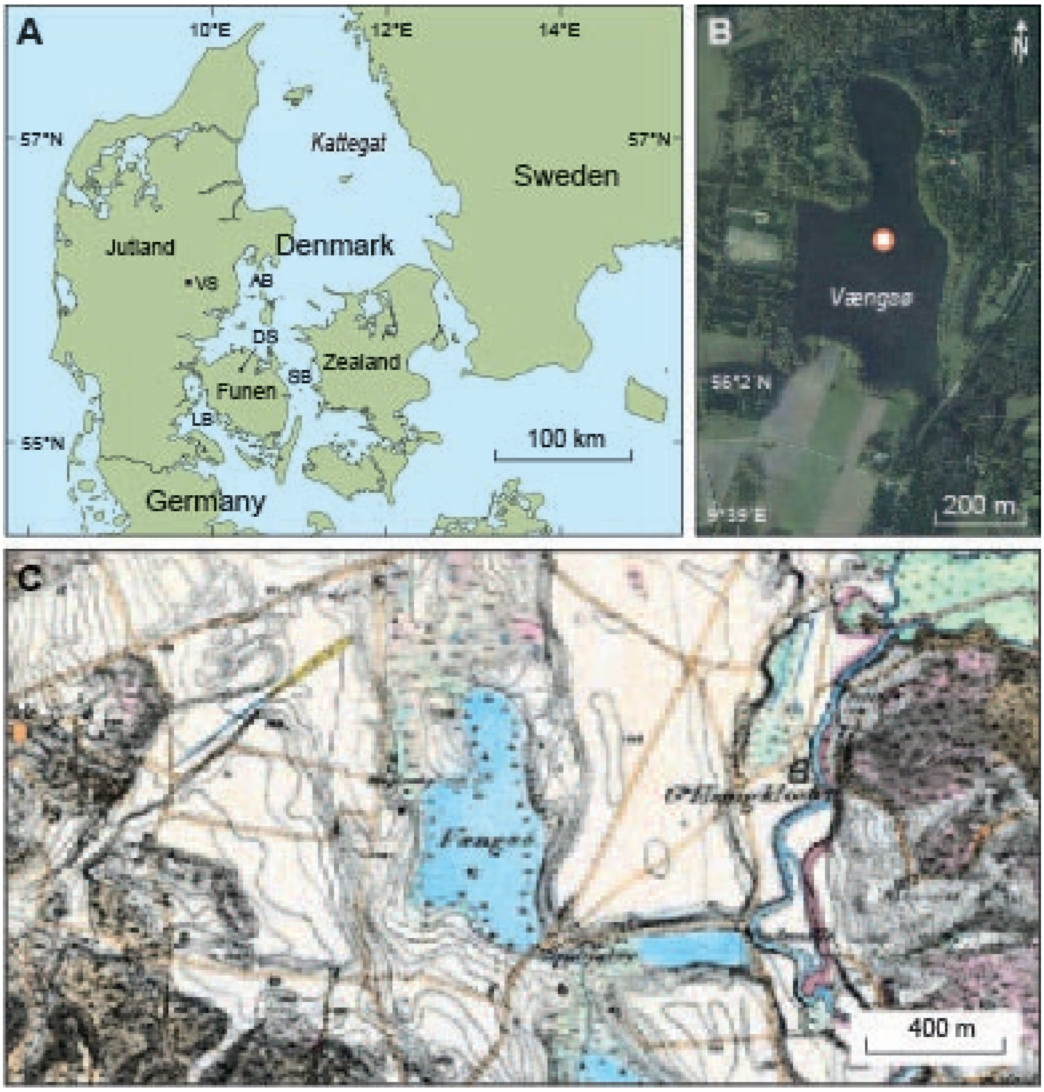

A
10°E
12°E
14°E
57°N
Kattegat
57°N
Sweden
Jutland
Denmark
VS
AB
DB
Zealand
SB
Funen
LB
55°N
100 km
Germany
B
N
Vængsø
200 m
C
400 m

Fig. 1

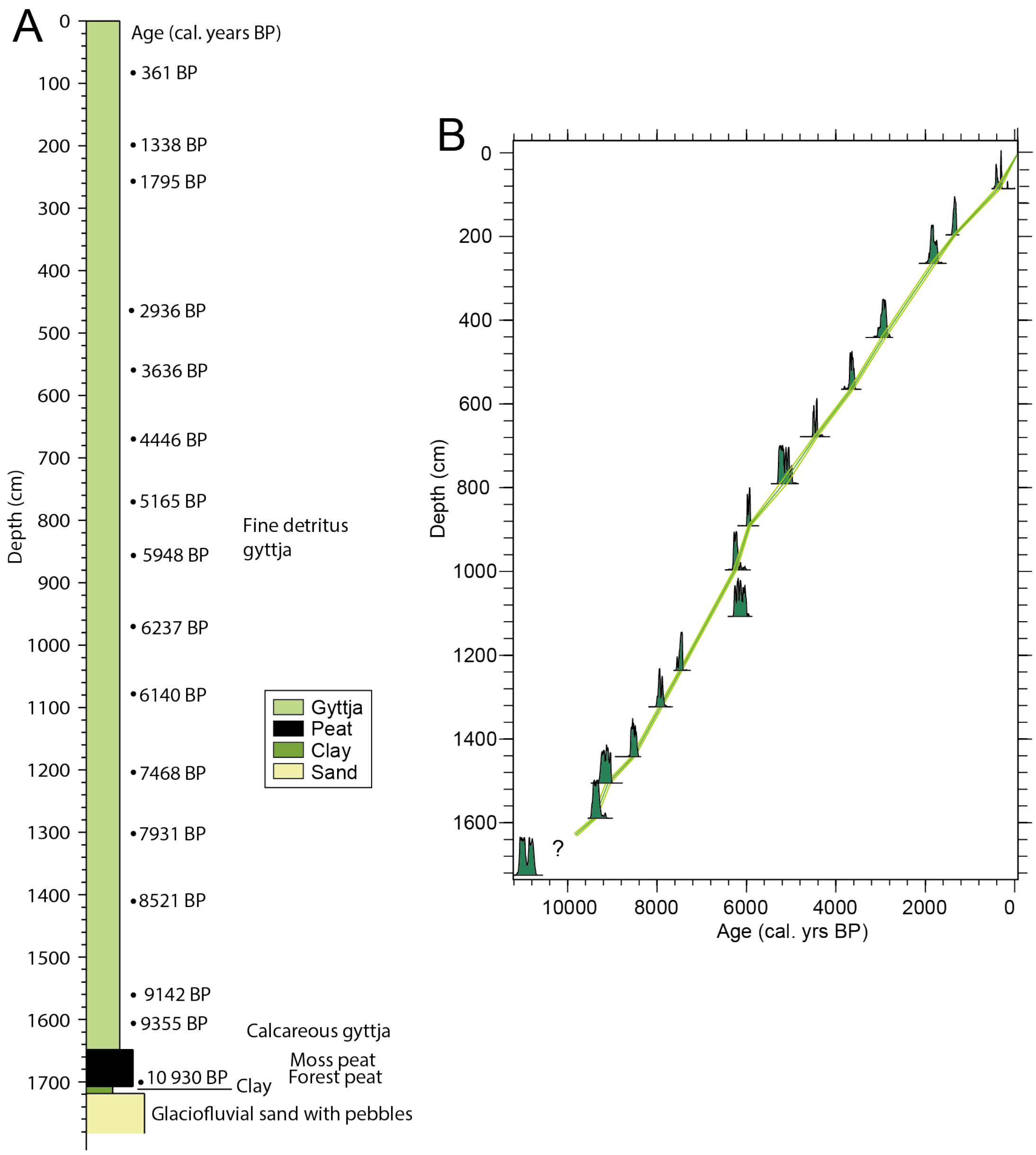
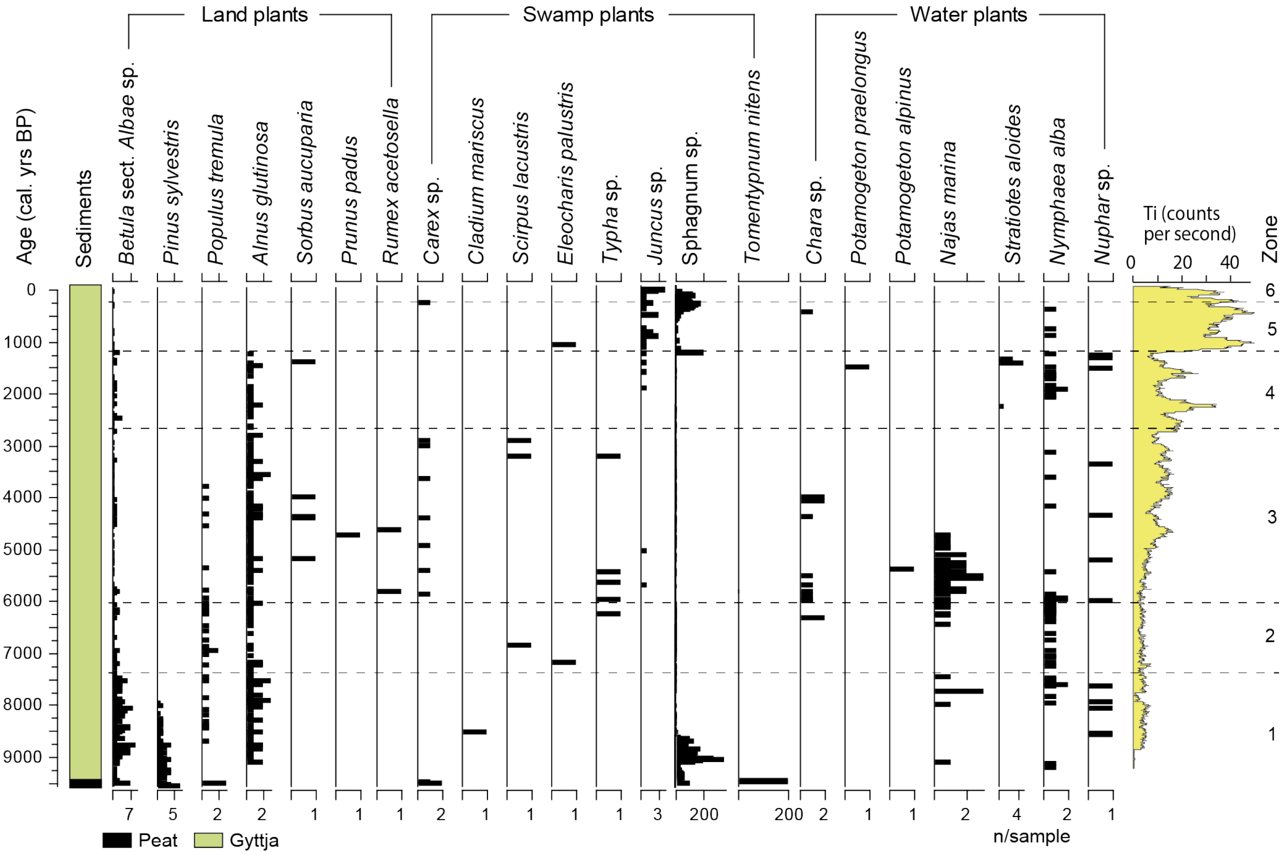
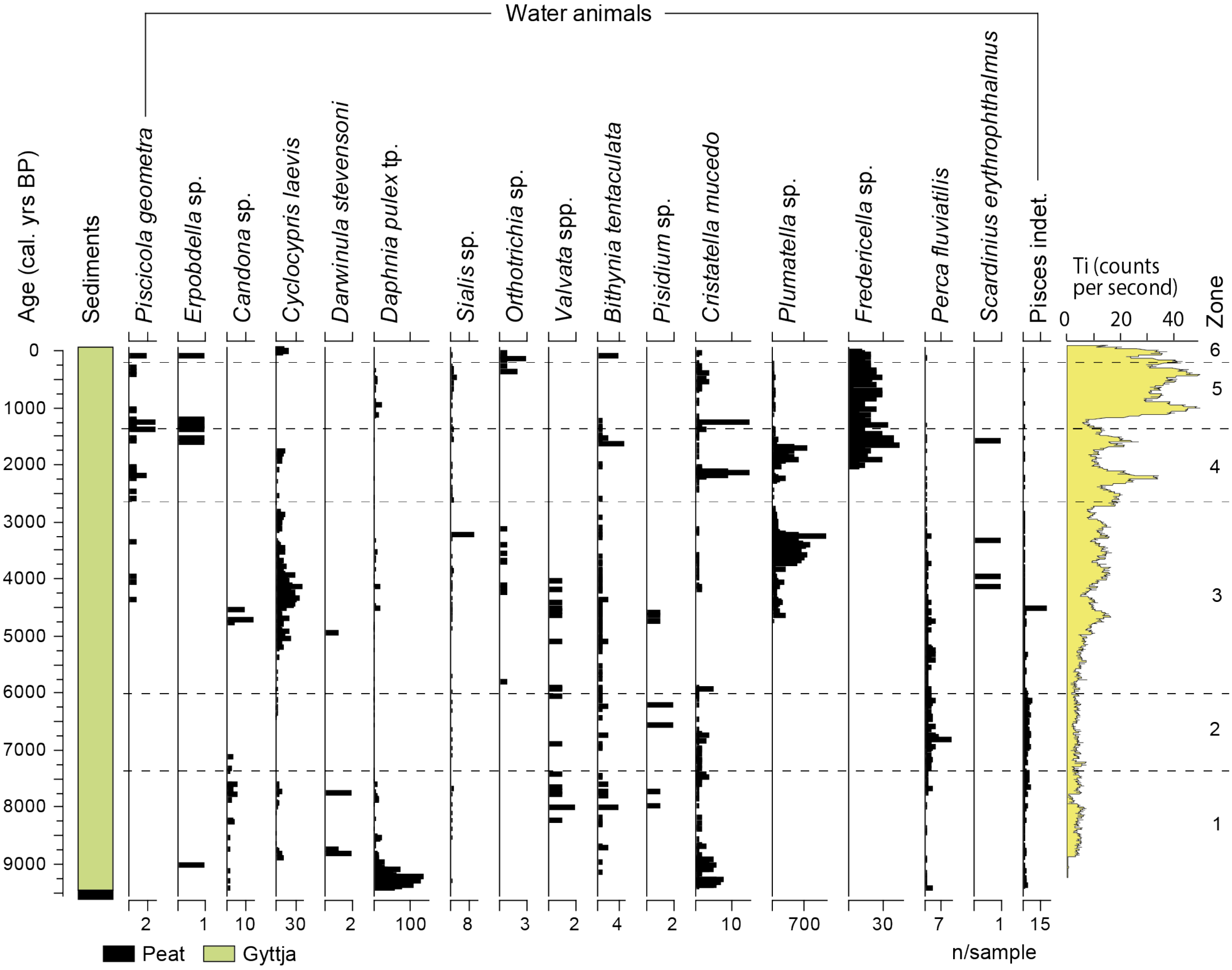

A
Age (cal. years BP)
Depth (cm)
361 BP
1338 BP
1795 BP
2936 BP
3636 BP
4446 BP
5165 BP
5948 BP
6237 BP
6140 BP
7468 BP
7931 BP
8521 BP
9142 BP
9355 BP
10 930 BP
Fine detritus gyttja
Calcareous gyttja
Moss peat
Forest peat
Clay
Glaciofluvial sand with pebbles
Gyttja
Peat
Clay
Sand
B
Depth (cm)
Age (cal. yrs BP)
?

Fig . 2



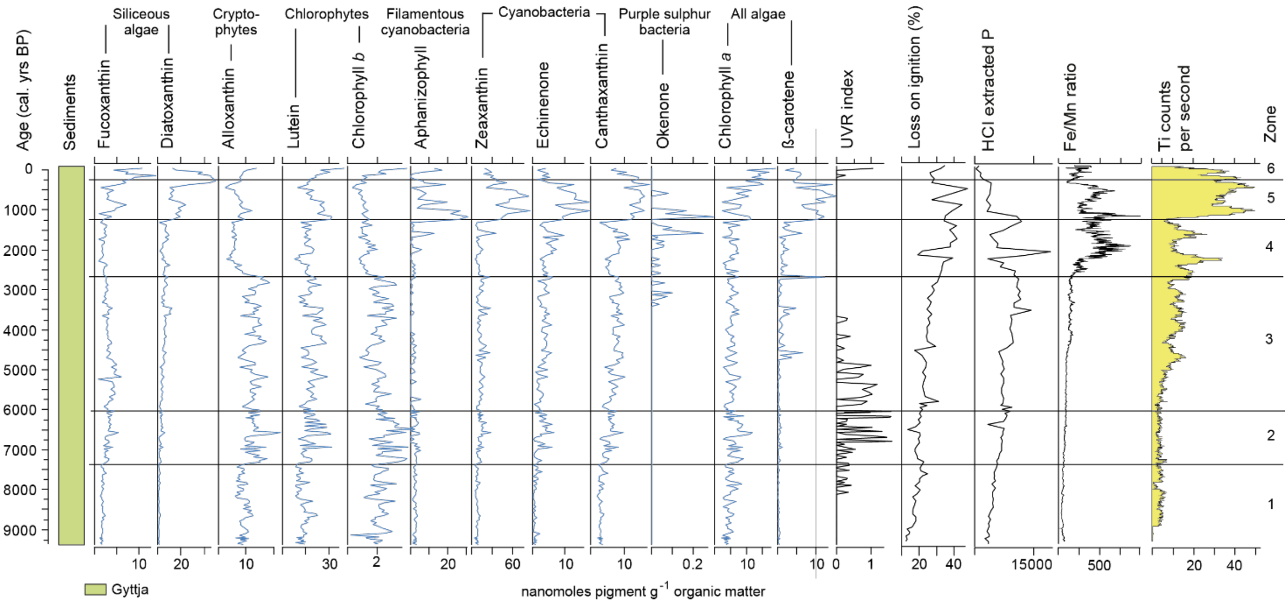
1169

1170 Fig. 3



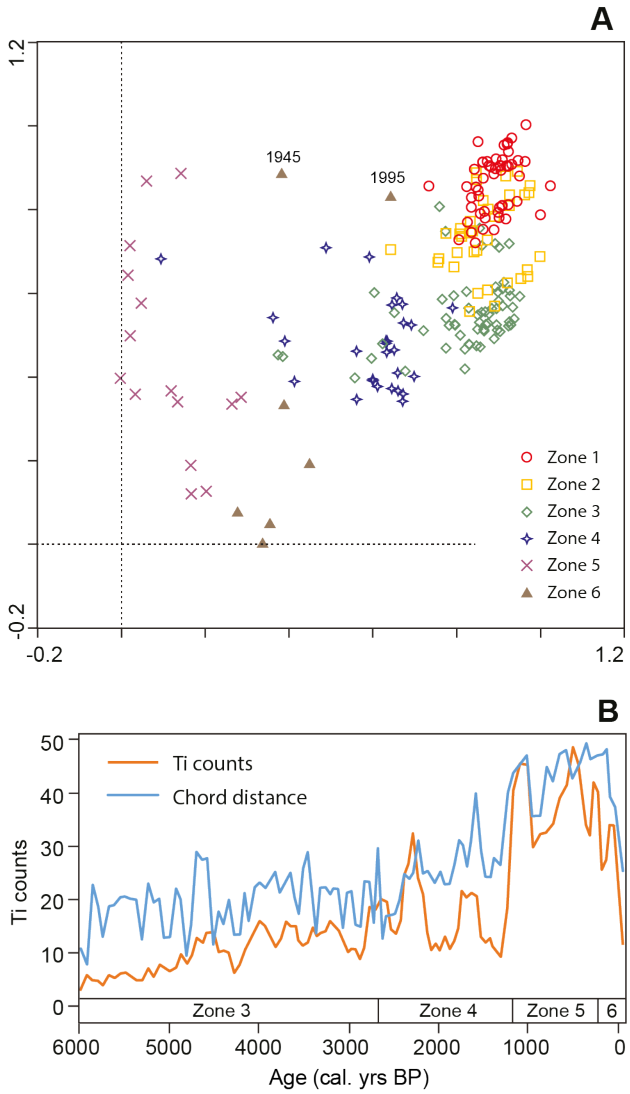
1171

1172 Fig. 4



1173

1174 Fig. 5



1175

1176 Fig. 6

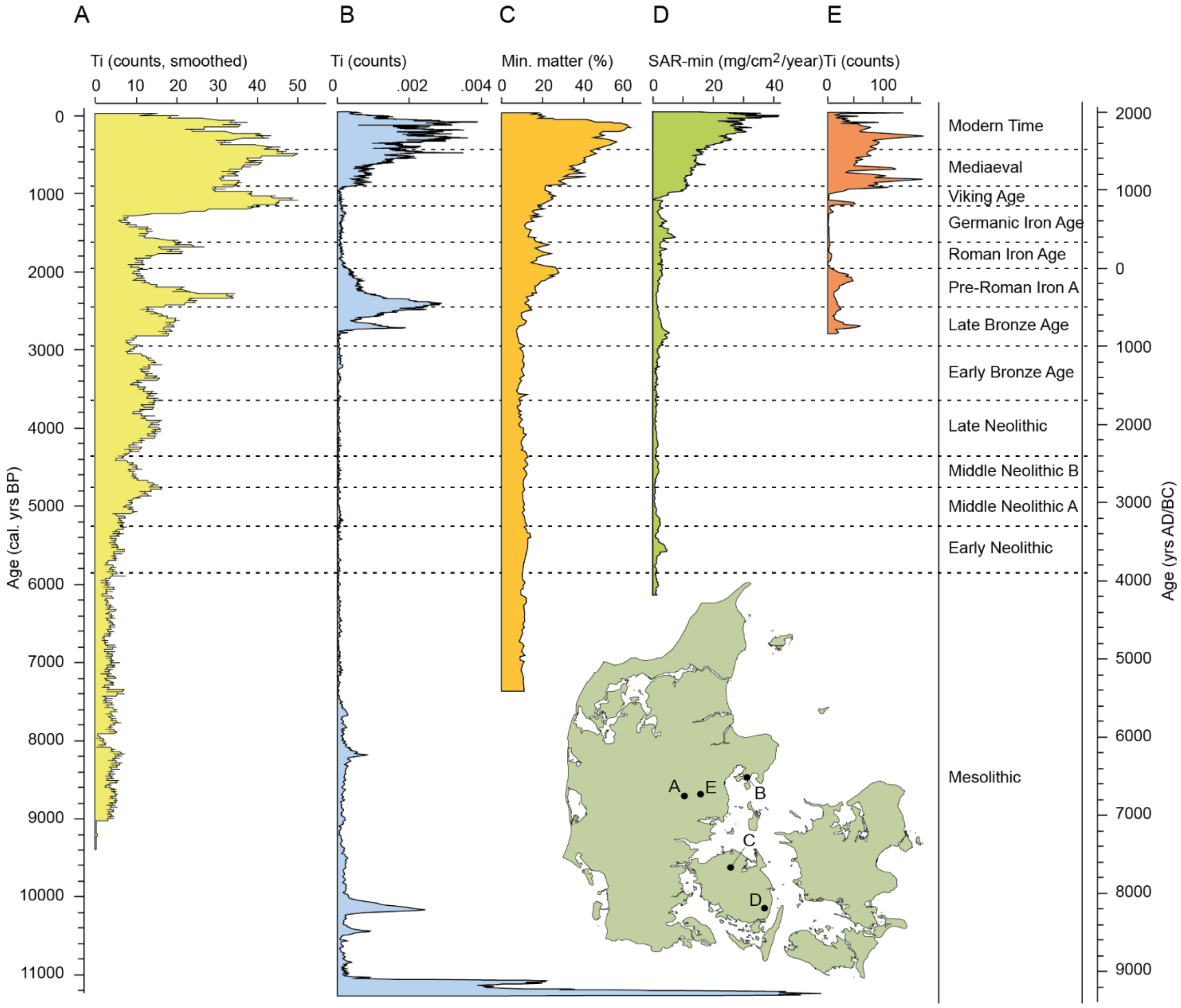

A
B
C
D
E
Ti (counts, smoothed)
Ti (counts)
Min. matter (%)
SAR-min (mg/cm2/year)
Ti (counts)
Age (cal. yrs BP)
Age (yrs AD/BC)
Modern Time
Mediaeval
Viking Age
Germanic Iron Age
Roman Iron Age
Pre-Roman Iron A
Late Bronze Age
Early Bronze Age
Late Neolithic
Middle Neolithic B
Middle Neolithic A
Early Neolithic
Mesolithic

Fig. 7

Supplementary

Early historical forest clearance caused major degradation of water quality at Lake Væng, Denmark

Table S1
AMS radiocarbon ages from Lake Væng, Denmark

Laboratory number	Depth (cm)	Material[a]	^{14}C age[b] (yrs BP)	Cal. age[c] (cal. yrs BP)	Cal. age[d] (cal. yrs BP)
AAR-24956	82–86	*Nymphaea alba*	275 ± 30	154–443	361
AAR-24957	194–198	Leaf fragments	1456 ± 29	1301–1381	1338
AAR-24958	262–266	*Betula* sect. *Albae*	1886 ± 45	1707–1924	1795
AAR-24959	442–446	*Betula* sect. *Albae*	2830 ± 40	2805–3069	2936
AAR-24960	558–562	*Alnus glutinosa*, BA	3400 ± 30	3564–3815	3636
AAR-24961	670–674	Leaf fragments	3972 ± 28	4300–4522	4446
AAR-24962	766–770	Leaf fragments	4477 ± 32	4978–5290	5165
AAR-24963	866–870	Bark fragment	5189 ± 29	5905–5996	5948
AAR-24964	966–970	Ag, BA, Na	5430 ± 46	6014–6307	6237
AAR-24965	1078–1082	Leaf fragments	5359 ± 50	6000–6280	6140
AAR-24966	1206–1210	*Betula* sect. *Albae*	6562 ± 38	7422–7566	7468
AAR-24967	1306–1310	Ag, BA	7101 ± 46	7838–8013	7931
AAR-24968	1410–1414	AG, *Pinus sylvestris*	7750 ± 37	8430–8593	8521
AAR-24969	1522–1526	Ps, BA, Ag	8196 ± 38	9022–9277	9142
AAR-24970	1606–1610	BA, Ps	8335 ± 44	9143–9474	9355
AAR-24971	*c.* 1662	Twig	9562 ± 34	10 725–11 090	10 930

[a] Full names are BA: *Betula* sect. *Albae* sp., Ag: *Alnus glutinosa*, Na: *Nymphaea alba*, Ps: *Pinus sylvetris*. The leaf fragments originate from deciduous woody plants.
[b] Radiocarbon ages are reported in conventional radiocarbon years BP (Stuiver and Polach, 1977). The ^{14}C ages have been corrected for isotopic fractionation to a δ^{13}C value of –25 ‰.
[c] Calibration to calendar years is according to the INTCAL20 data (2 sigma).
[d] Mean probability ages.

Core correlations

In the field the depths of the core sections were noted. The Kajak discrete samples, the Russian cores and the Usinger A and B cores overlaps in depth so they all together cover a continuous series of 16.30 m from the top of the sediment. The Kajak core was subsampled into 14 samples of 2 cm covering the top 28 cm of the sediment. The three Russian cores were each 1 m long overlapping in depth 18-20 cm, and XRF logged to respectively 10 to 110 cm, 90 to 190 cm, and 170 to 270 cm. The Usinger cores were 2 m long. The first Usinger A cores was retrieved from a logged depth of 180 to 380 cm, and the following six Usinger A cores were retrieved from continuing depths. The Usinger B cores were shifted 50 cm in depth relative to the A cores with the first Usinger B cores retrieved from a logged depth of 230 to 430 cm, and the following six Usinger B cores from continuing depths.

In the XRF records the top of the sediment in each 2 m section of the Usinger A cores was assigned the depths from the top of the sediment, which was 175 cm below the water surface, of respectively 1800, 3800, 5800, 7800, 9800, 11800 and 13800 mm. The Usinger B cores were correlated to the A cores using variations in the records of density proxy, Fe, Zr, radiography grey scale and magnetic susceptibility. The density proxy come from the ratio between the photon count numbers of the Rayleigh and the Compton scatter peaks in the XRF spectra, while the radiography grey scale come from the mean pixel value across the radiography image. The grey scale varies from core to core due to different thickness of the core half used for XRF scanning; however, variations in the grey scale on a depth scale below 1 m are useful for core correlations.

Table S2 shows the correlation points between all the cores. The depths listed in the table are measured from the logging depth at the top of the sediment in each core segment. The core segments of the Usinger A and B cores are indicated with colours.

Usinger A extended to the top of the sediment

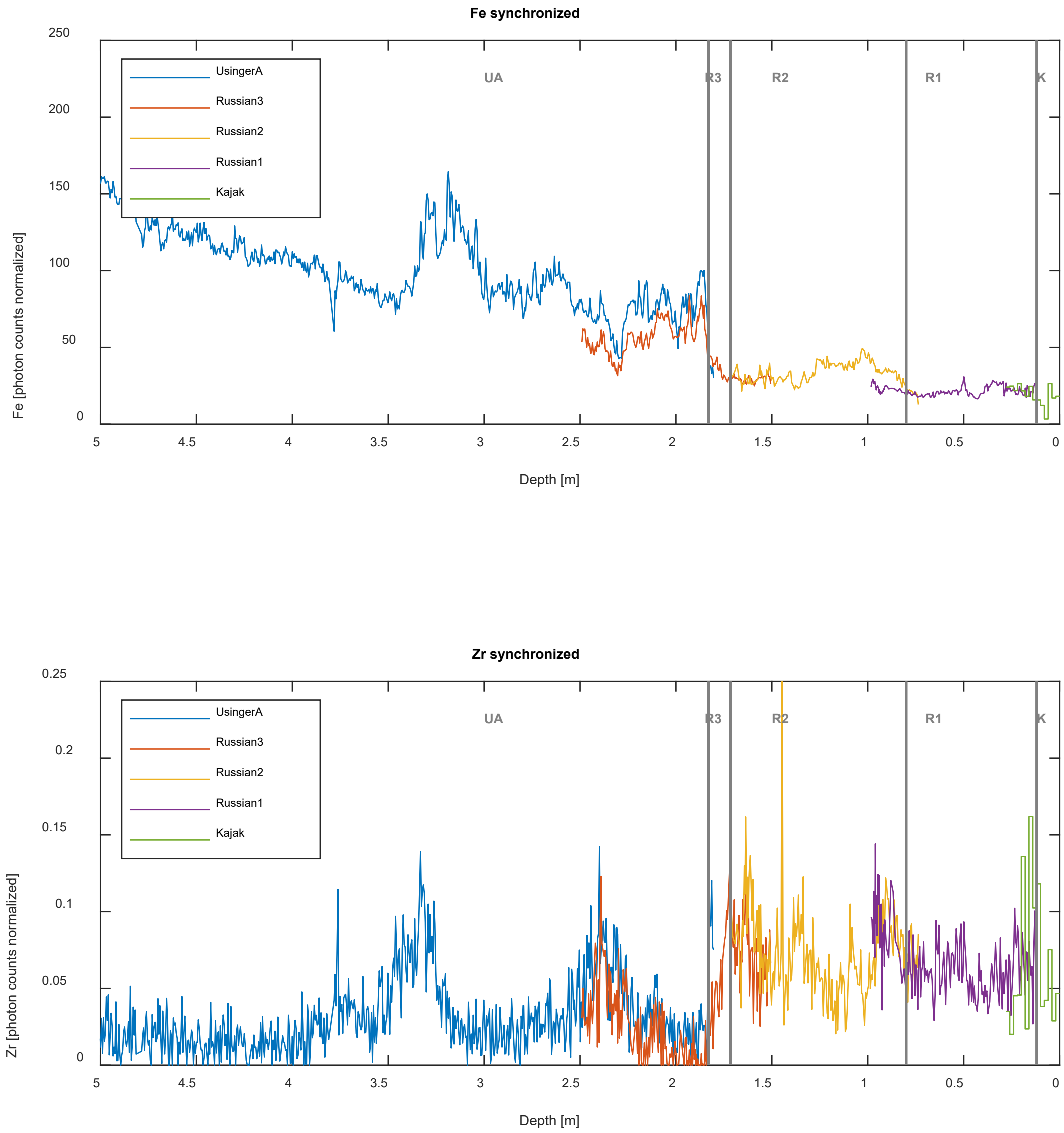


Figure S1: Extention of Vængsø Usinger A core to the top of the sediment with the Russianb1,2, 3 cores and discrete Kajak samples at the top. The top figure shows the upper 5 m of the iron record while the bottom figure shows the upper 5 m of the zirconium record. The vertical lines indicate the sections where cores labeled K: Kajak, R1,R2,R3: Russian1,2,3 and UA: Usinger A was used in the extension.

UsingerA and UsingerB on the same depth scale

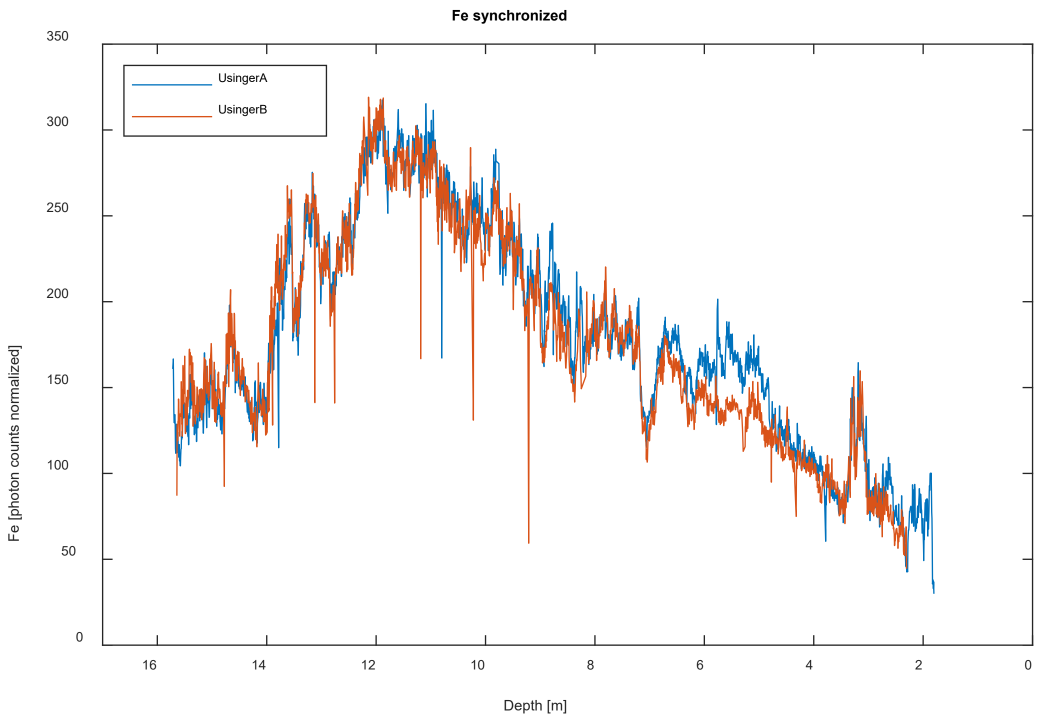


Figure S2: Iron records of Lake Væng Usinger A and Usinger B, on the Usinger A depth scale. The Usinger B was correlated to Usinger A using linear interpolation between 123 correlation points.

Kajak	Russian 1	Russian 2	Russian 3	Usinger A	Usinger B
0					
120	100				
	780	965			
	830	1080			
	945	1135			
		1695	1720		
		1745	1765		
		1785	1810		
		1860	1860		
		1880	1910		
			2030	1831	
			2131	1905	
			2189	1955	
			2222	2018	
			2346	2144	
			2376	2177	
			2414	2208	
			2460	2283	
				2341	2342
			2595	2394	
				2401	2418
				2438	2459
				2519	2516
				2546	2542
				2572	2563
				2639	2597
				2674	2648
				2714	2665
				2746	2716
				2774	2745
				2836	2840
				2867	2878
				2885	2894
				2913	2927
				2990	3015
				3029	3066
				3051	3096
				3074	3110
				3135	3133
				3172	3180
				3207	3214
				3237	3237

				3261	3269

Table S2: Correlation points for synchronizing the Lake Væng cores to the Lake Væng Usinger A.

Usinger A	Usinger B		Usinger A	Usinger B		Usinger A	Usinger B
3332	3342		8472	8455		13471	13656
3386	3382		8530	8530		13530	13719
3412	3425		8605	8606		13634	13811
3541	3556		8646	8658		13713	13898
3652	3667		8677	8699		13995	14481
3703	3704		8737	8756		14685	15153
3768	3752		8767	8791		14748	15251
3916	3895		8828	8830		14822	15330
3996	3997		8997	9005		15028	15553
4062	4046		9041	9066		15148	15690
4116	4107		9106	9184		15376	15953
4229	4171		9180	9263		15485	16079
4383	4341		9243	9298		15548	16170
4482	4448		9391	9438			
4626	4560		9538	9579			
4707	4654		9579	9622			
4765	4718		9661	9726			
4944	4962		9855	9929			
5021	5043		10009	10045			
5254	5394		10146	10163			
5512	5504		10277	10328			
5618	5596		10349	10361			
5745	5755		10400	10418			
5915	5908		10542	10512			
6009	6018		10629	10570			
6160	6187		10729	10682			
6426	6354		10831	10812			
6725	6567		10902	10975			
6811	6827		11384	11473			
6920	6930		11469	11577			
7054	7075		11604	11708			
7165	7178		11907	11967			
7291	7316		12299	12377			
7449	7474		12381	12477			
7616	7598		12451	12562			
7729	7739		12536	12661			
7830	7855		12639	12746			
7901	7929		12713	12835			
7967	7985		12843	12965			
8027	8062		13016	13175			

8071	8109		13175	13353			
8250	8311		13323	13486			
8342	8391		13427	13589			

Table S3: Table S2 continued.

Reference

Stuiver, M., Polach, H.A., 1977. Discussion of reporting ^{14}C data. Radiocarbon 19, 355–363. https://doi.org/10.1017/s0033822200003672