Dendroökologische Untersuchungen an subfossilen Moor-Kiefernwäldern in Niedersachsen

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Dendroecological investigations on subfossil mire pine woodland in northwest Germany

Dissertation
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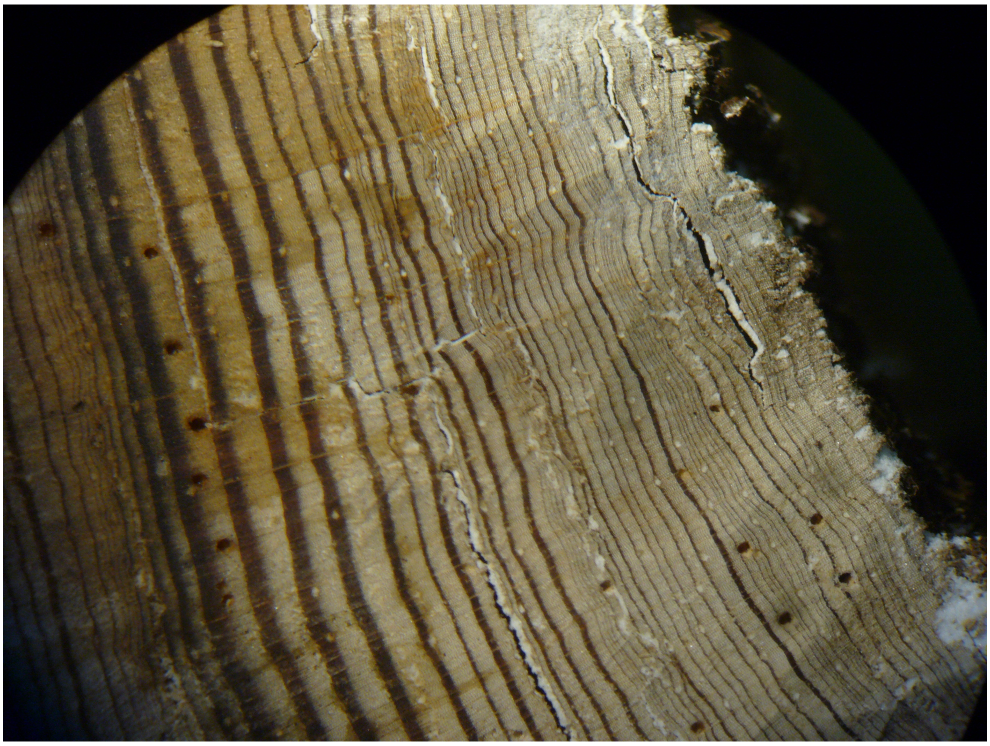

Pine sample *M92315* from *Gifhorner Moor* (Photo: Inke Achterberg)

In memory of my father, Dr. Bernhard Achterberg (1945-1998)

and his memory of his mother, Dr. Elisabeth Achterberg-von Pusch (1913-1980)

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Contents

Additional research

Abbreviations

BC	–	Before Christ
AD	–	Anno Domini
TRW	–	Tree Ring Width
LSBOC	–	Lower Saxony Bog Oak Chronology
LSBPC	–	Lower Saxony Bog Pine Chronology
die-off rate a-30	–	Number of trees dying off in a year divided by sample depth 30 years previously

Abstract

The present work is a dendrochronological investigation of peat-preserved pines (*Pinus sylvestris*) from northwest German mires (Fed. State of Lower Saxony). The project (DFG funded project LE 1805/2-2) continued the work of the predecessor project (DFG funded project LE 1805/1-2), which had begun the dendrochronological survey of the pines. Oak chronologies composed of wood from mires and river deposits had been established earlier.

The pines contain environmental indications complementary to those supplied by the oaks. This is one of the reasons to intensely investigate them. The pine remains are a common feature in Northwest-German mires, occurring mostly in extended layers at the fen-bog-transition. Therefore, they provide indications on the phases of enhanced raised bog expansion and formation. The dendrochronological record of peat-preserved pines has already provided major insights towards the temporal history of raised bog formation in northwest Germany.

The work presented here continued the work on the pine chronology and the evaluation of the inherent environmental indications:

A method for the quantification of a signal of water table rise and mire expansion in the trees was developed and investigated it in context of archaeological finds (wooden mire bridging trackways) from the region which are dated equally precise (manuscript 1).

The pine chronology was extended, and the gaps therein reduced considerably. Over all, the number of dendrochronological dated pine trees has been more than doubled (to over 3000 trees), two of four gaps were closed, the total gap length was reduced from 1705 years to 170 years and the cover of the pine chronology was extended by 1771 years, now covering 5369 years and reaching 220 years further into the past. The well-replicated pine chronology has become a considerable dating tool and environmental record (manuscript 2).

In a case study, the spatio-temporal development of raised bog was reconstructed. This was uniquely possible using the dendrochronological dating of areal exposed in situ pine remains. In a case study at the mire *Totes Moor* near Hanover, 210 dated in situ and not-displaced tree remains were used for a spatio-temporal reconstruction of the lateral raised bog expansion across some 500 m (SE-NW) between c. 6600 and 3400 BC (manuscript 3).

Zusammenfassung

Die vorliegende Arbeit ist eine dendrochronologische Untersuchung an in Torf erhaltenen Kiefern (*Pinus sylvestris*) aus Nordwestdeutschland (Niedersachsen). Das Projekt (DFG gefördertes Projekt LE 1805/2-2) führt die Arbeit des Vorgängerprojektes (DFG gefördertes Projekt LE 1805/1-2) fort, welches die dendrochronologische Untersuchung der Kiefern begonnen hatte. Eichen-Chronologien bestehend aus Holz aus Mooren und Flussbetten waren schon früher aufgebaut worden.

Die Kiefern enthalten Umweltsignale die diejenigen der Eichen ergänzen. Dies ist einer der Gründe, sie intensiv zu untersuchen. Die Überreste der Kiefern sind eine häufige Erscheinung in nordwestdeutschen Mooren, die hauptsächlich am Niedermoor-Hochmoor-Übergang in ausgedehnten Lagen vorkommen. Daher liefern sie Informationen zu Phasen verstärkter Hochmoorausdehnung und – Bildung. Der dendrochronologische Datensatz der Kiefern aus Torferhaltung hat bereits maßgebliche Erkenntnisse zum zeitlichen Ablauf der Hochmoorentwicklung in Nordwestdeutschland beigetragen.

Die vorliegende Studie setzt die Arbeit an der Kiefern-Chronologie und der Auswertung der enthaltenen Umwelt-Signale fort:

Eine Methode, um die Indikationen für Wasserspiegel-Anstieg und Moorwachstum aus den Bäumen zu quantifizieren, wurde entwickelt und diese im Kontext ebenso exakt datierter archäologischer Funde (hölzerner Moorwege) aus derselben Region betrachtet (Manuskript 1).

Die Kiefern-Chronologie wurde erweitert, und darin verbliebene Lücken weitgehend geschlossen. Insgesamt wurde die Anzahl datierter Kiefern mehr als verdoppelt (auf über 3000 Bäume), und zwei von vier Lücken in der Chronologie wurden geschlossen. Die Gesamtlänge der Chronologie-Lücken wurde von 1705 Jahren auf 170 Jahre verringert und die Chronologie um 1771 Jahre erweitert, wodurch sie nun 5369 Jahre umfasst und 220 Jahre weiter in die Vergangenheit zurück reicht. Die gut belegte Chronologie ist zu einem relevanten Datierungs-Instrument und Umweltarchiv geworden (Manuskript 2).

In einer Fallstudie wurde eine räumlich-zeitliche Rekonstruktion der Hochmoorentwicklung erstellt. Dies war möglich durch die dendrochronologische Datierung flächig freigelegter in situ Kiefernstümpfe. Im Toten Moor nahe Hannover wurden 212 datierte in situ s.l. Baumreste für eine räumlich-zeitliche Rekonstruktion der flächigen Hochmoorausdehnung auf einer Fläche von ca. 500 m Breite (SO-NW) im Zeitraum zwischen rund 6600 und 3400 v. Chr. verwendet (Manuskript 3).

Introduction

Large mires, particularly huge flatland raised bogs, had dominated the Northwest-German landscape for large parts of the Holocene (Behre 2008). The dynamic of their development and growth is closely linked with climatic conditions (e.g. Eckstein 2009, Ellenberg 1996).

Microbial decomposition is minimized in these wet environments, due to lack of oxygen and acidity. This results in the accumulation of peat from the local plant matter and the preservation of organic enclosures within, such as pollen, wood or archaeological artefacts. The mires therefore provide insights into the past.

In the (formerly) mire rich region (Fed. State of Lower Saxony), large scale industrial peat extraction uncovered the preserved remains of numerous tree stumps and stems. In dendrochronological research, they form an environmental record of the Holocene with immanent precise dating, beside being a dating-tool for other wooden finds as well.

The vast majority of these are pine (*Pinus sylvestris*), which typically occur at the fen-bog-transition (Eckstein et al. 2011, Ellenberg 1996).

The remains of oak trees (*Quercus* spec.) are also to be found, which have been subject to dendrochronological research in Northwest-Germany for decades before the pine remains of the region were studied as well. The oak trees, which, as a ring-porous deciduous species, can be relied on forming a ring each year, have formed the strong backbone of dendrochronological dating in the region. The Lower Saxony Bog Oak Chronology (LSBOC), which has been constructed in Göttingen, to date spans from 6628 to 6178 BC and from 6069 BC to 931 AD (manuscript 2). The dating is secured by a tree-ring chronology of historical and archaeological material which spans 610 BC – 2013 AD.

Based on the dating-tool the LSBOC offers, dendrochronological study of the peat-preserved pines started in 2006 (Leuschner et al. 2007). In the following years, the progressing construction of the Lower Saxony Bog Pine Chronology (LSBPC) was a result of DFG funded projects (LE 1805/1-2 and LE 1805/2-2) on the peat preserved pines (Eckstein et al. 2009, 2010, 2011, manuscripts 1 and 2). The pines, as evergreen conifers, can skip ring formation for one or several years when growth conditions are unfavourable, and also often limit ring-formation to (sometimes tiny) portions of the perimeter (figure 1). This is one of the reasons, why it was necessary to sample large numbers of pines and to construct well replicated floating site chronologies. Only then it was possible to absolute-date the pine chronologies on base of the LSBOC. As both, the oak material of the LSBOC and the pine material discussed here (LSBPC), originate from the mires of northwest Germany

Figure 1: Wedging rings (Pine sample M92315, from *Gifhorner Moor*). Arrows mark conversion points. Hollow arrows indicate re-appearances of a ring already marked by a solid arrow. Photo: Inke Achterberg.

(Lower Saxony), the chronologies share common signals and cross date well with one another. As the cover by the LSBPC extended, the pines were dated on base of the pine chronology directly with increasing frequency. Eventually, even an extension of the oak chronology (LSBOC) was made by being dated on base of the pine chronology (LSBPC) in turn (manuscript 2).

The study presented here is the continuation of the work of Eckstein et al. (2009, 2010, 2011), who have established the pine chronology in large parts. Eckstein at al. (2009) described the population dynamics of the pines, which show pronounced germination and die-off phases. They also discovered the vast synchronicity of these phases in different mire systems, which emphasises the climatic signal therein. They were able to identify water table rise as the prevailing cause of death, deducted from root morphology and other indicators, such as peat stratigraphical properties (Eckstein et al. 2010). For the common occurrence of the trees at the base of raised bog peat, they also dated the beginning of raised bog development in Northwest-Germany to c. 7000 BC and identified a main phase of raised bog development between 5100 BC and 3600 BC (Eckstein et al. 2011).
The more recent work presented here is focussed on using the environmental indications to be gained from the trees, complementing the chronology, and on the spatio-temporal reconstruction of raised bog development.

Study area: the mires of the Northwest-German lowland

The NW-German lowland is an rather flat area of sandy plateaus of low elevation (*geest*), and even lower lying marshlands, both in large parts covered by peatlands. It's northern border is the coastline of the North Sea. To the south the lowland meets the fringe of the Central German Upland, a mesozoic sandstone (*Roeth*) and limestone hill formation, where rich soils occur, namely thick layers of *loess* at it's fringe. Northeast of the study area the land is less flat (a young moraine landscape), and more continental conditions persist towards southeast of it, which is why large bogs are in result mostly missing there. West of the study area, the boggy lowland continues in the Netherlands.

The sandy base of the lowland is rather flat and particularly poor in nutrients. The sands are glacial deposits from earlier glaciations (Elster and Saalian Ice Ages). While during the last (Weichselian) glacial, the area remained ice-free, under the periglacial conditions. Unprotected by ice or sufficient plant cover during that time, erosion levelled the plain, fine particles (*loess*) got blown away and nutrients were washed from the surface. After the last glacial cold period, these conditions, together with climatic humidity, favoured the development of the large lowland raised bogs, that later became characteristic for the area.

During the Holocene (present warm period), numerous mires developed and expanded, covering former lakes and forests. Favoured by the humid climate, many small mires fused as they grew to form extended fens and raised bogs. The large lowland raised bogs in some cases exceeded 100 km^2 in size and accumulated peat more than 10 m high. To differ between the two mire-types is important, as their ecology and hydrology differ greatly as well. Fens are minerotrophic mires, which stand in context with ground water. They are therefore more rich in nutrients. Their hydrology is affected by fluctuations of groundwater level, which can be linked to sea level changes, besides effective precipitation (Behre 2008). Raised bogs in contrast are rainfed (ombrotrophic) mires, which depend on precipitation and are hence very nutrient poor environments. They are largely formed by the *sphagnum* mosses, which create acidic conditions around them. *Sphagnum* cushions can lift the water table high above the surrounding as they grow. They can over-grow other vegetation, even woods, when conditions favour them. Their centre is usually tree-less in the region, while they can support large trees at their margin or in very dry periods (Ellenberg 1996, Overbeck 1975).

Raised bogs developed on the sandy ground directly or atop fen-peat. The latter is the common succession after the mire surface is disconnected from the groundwater. This is often a result of fen-peat accumulation, but can also be due to a lowering of groundwater level. Therefore, the meteorological context of a fen-bog-transition is not necessarily always high effective precipitation alone, which enhances peat accumulation and nutrient wash-out from the surface, but can also be related to a preceding dry phase, which lowers the ground water level and thereby cuts nutrient-supply to the surface (Hughes 2004, Tahvanainen 2011). Particularly wet-dry-wet sequences are mentioned in this context (von Bülow 1935).

The spread of the raised bogs largely took place after 6000 BC, when the climate generally got more humid (Overbeck 1975). Increasing humidity in the area during the Holocene was not only result of the global climatic variations. Also, the glacial melt-water caused sea level rise over millennia, gradually filling the southern basin of the North Sea. The North Sea Transgression took place rather fast (about 14 cm/y) until around 3500 BC, and in alternating trans- and regressions of various intensity after that (Behre 2008). Together with the coastline, maritime conditions advanced further south-east. It also halted water run-off, which promoted the fens of the river basins and other sites affected by ground-water rise (Frohne 1962). While the sea approached from the north, more and more of the inland turned into mires. Close to a third of the study area was eventually covered by wetlands (Metzler 2004), made up of about 3500 km^2 raised bogs and c. 2800 km^2 fens at their maximum (Behre 2008). In approximate accordance with these statements on landscape history, Eckstein at al. (2011) found the raised bog development in the region to have begun around 7000 BC and to have undergone a main phase from 5100 BC to 3600 BC, based on dendrochronological data. In the first century AD, peat cutting was already a common practice in the region (Pliny t.e., Overbeck 1975). Today the large bogs are drained and converted to farmland or still being mined, some are being re-wetted.

Pines in the mires

The stratigraphic position of the pines at the fen-bog-transition (Ellenberg 1996, Eckstein et al. 2009, 2010, 2011) was observed for the vast majority of investigated in situ pine remains. This is in accordance with the typical stratigraphy described for German mires (Overbeck 1975, Ellenberg 1996). The pine woodland often grew on layers of fen peat, and were preserved under sphagnum peat, which often was preceded by an *Eriopherum* rich phase. Investigations i.a. in the *Dümmer* basin, at *Venner Moor* and *Campemoor*, (Eckstein et al. 2010) encountered many specimen rooting down into the sand below the peat. In contrast, the pines investigated e.g. at the Tote Moor turned out not to reach the mineral base with their roots (manuscript 3). Hence, both situations can be encountered with likelihood. The occurrence of pine layers within raised bog peat is much less frequent. Most of such cases we encountered featured small stumps of ca. 10-15 cm diameter. These had to few rings to be securely dated by dendrochronology in the sampled cases. But also large trees rooting on thick raised bog peat occur, for example at *Gifhorner Moor*, where such a case had been described by Overbeck (1952) and was sampled in situ within the frame of the present study. Such a case of large pine trees with numerous rings rooting in considerable layers of sphagnum peat is rare in the region, judging from literature (e.g. Overbeck 1975). Even slimmer are the chances of encountering such a tree layer today, because the upper layers of sphagnum peat have been removed in most places. Some of the ex situ tree remains, which are gathered from waste piles of the peat mining industry, may have originated from such upper tree layers. As the peat mining is required by law to leave a meter of grown peat standing at the sites, the pine layers from the fen-bog transition often serve as the practical termination of extraction activity and are hence accessible in situ.

The position of most of the preserved pine remains at the fen-bog transition determined the indication they provide: dating the pines meant dating the bog development. This was largely the areal lateral expansion of raised bog over fen peat. The dating of the trees, particularly their die-off dates, would provide a dating of areal bog expansion, including indications to its speed and uniformity. This was the main indication of the temporal tree distribution acquired by dendrochronological dating. Furthermore, spatio-temporal investigation of raised bog expansion was possible, provided sufficient in situ trees.

The temporal distribution of the trees and the related raised bog expansion reflect a climatic signal. This was affirmed by the phase wise occurrence and the synchronicity of such phases in different mires of the region (Eckstein 2009, 2011).

Research objectives

The present study was conducted towards the following aims:

1. Eckstein et al. (2009, 2010, 2011) had observed the pine material to contain environmental and climatic indications. Therefore, the large data set of the peat-preserved trees was to be used as a environmental record.
2. The work on the pine chronology from Northwest-German mires, established by Eckstein et al. (2009, 2010, 2011), was to be continued. The gaps were to be closed as far as possible, the time covered to be expanded, if possible, and the replication was to be improved, in order to receive a more valuable base for dendrochronological dating and environmental assessment.
3. Pine layers from the fen-bog-transition were found to date the local beginning of raised bog development by their deaths (Eckstein et al., 2009, 2010, Edvardsson et al., 2014, Leuschner et al., 2002, 2007). Therefore, the precise dating and known location of such in situ tree remains was to be used for a spatio-temporal reconstruction of raised bog development in a case study.

Synthesis

The pine chronology and tree ring archive were substantially extended (manuscript 2) and evaluated for environmental indications (manuscripts 1 and 3). The die-off phases of the trees indicate phases of bog expansion. This was evaluated on a regional scale (manuscript 1), and locally for one site (manuscript 3), in that case including the spatial aspect.

The environmental signal of tree die-off phases from the whole set of peat-preserved pines from northwest Germany was combined with that of the peat-preserved oaks from northwest Germany for a regional signal (manuscript 1). This proxy, which indicates mire expansion and water table rise in the landscape, was evaluated in context of peat-preserved wooden trackways. Trackways with precise dendrochronological construction dates were used for the survey. This was done to investigate the temporal coherence of trackway construction with environmental change, which had been suggested by several authors.

The indication of the trees for mire expansion was also used in a case study (manuscript 3). In this case, raised bog formation was reconstructed in an areal investigation on one site. In the extended layer of pine stumps exposed at the site, numerous in situ trees were sampled and dated. These document the advancing margin of raised bog over time.

Pines as a regional environmental record

The trees contain a climatic record of their time, particularly plastic in their die-off dates. As described by Eckstein et al. (2011), the trees feature relatively distinct die-off phases, which are often synchronous in different mires and therefore clearly reflect climatic influence.

Therefore the die-off record of the dataset (pines and oaks in this case) was used as an environmental proxy, which was then applied to investigate the timing of dendrochronologically dated trackway constructions for coherence with environmental change (manuscript 1).

For the comparative use of a long chronology sequence as environmental implicative die-off record, the following conditions were to be considered: The replication of the chronologies is very heterogeneous over time (manuscript 2, Figure 5). This was a. o. a result of some sites having been subject to intense study, and some periods of tree growth only being represented by few individuals from site margins. This made it difficult to compare die-off frequency of different events and periods. The parameter of mean age, which had proven a sound variable long term comparisons of environmental stability (Leuschner et al. 2002), was equally inapt for the intended investigation, because germinations (new young trees entering the data set) take a substantial influence on mean age, while they did not reflect the environmental change in question here. These considerations led to the development of the 'die-off rate a-30', which sets die-off frequency in relation to replication of 30 years previously. The 30 years were set according to the dynamic in the dataset, aiming to capture a representative portion of the trees in the record that were potentially affected by the event. In that sense, the trees which had died off in previous events were not to be included in the divisor, for they would smudge the display of the die-off event at hand by adding unrelated variations of divisor size (replication).

In result, the die-off rate a-30 retains the timing of die-off events (as displayed by die-off frequency), but levels the hight of the die-off peaks by largely detaching them from replication (figure 2). Only at the end of chronology segments, where replication reaches 0, inadequate values were obtained. The transformation achieved some level of comparability between events, despite the heterogeneous composition of the data set.

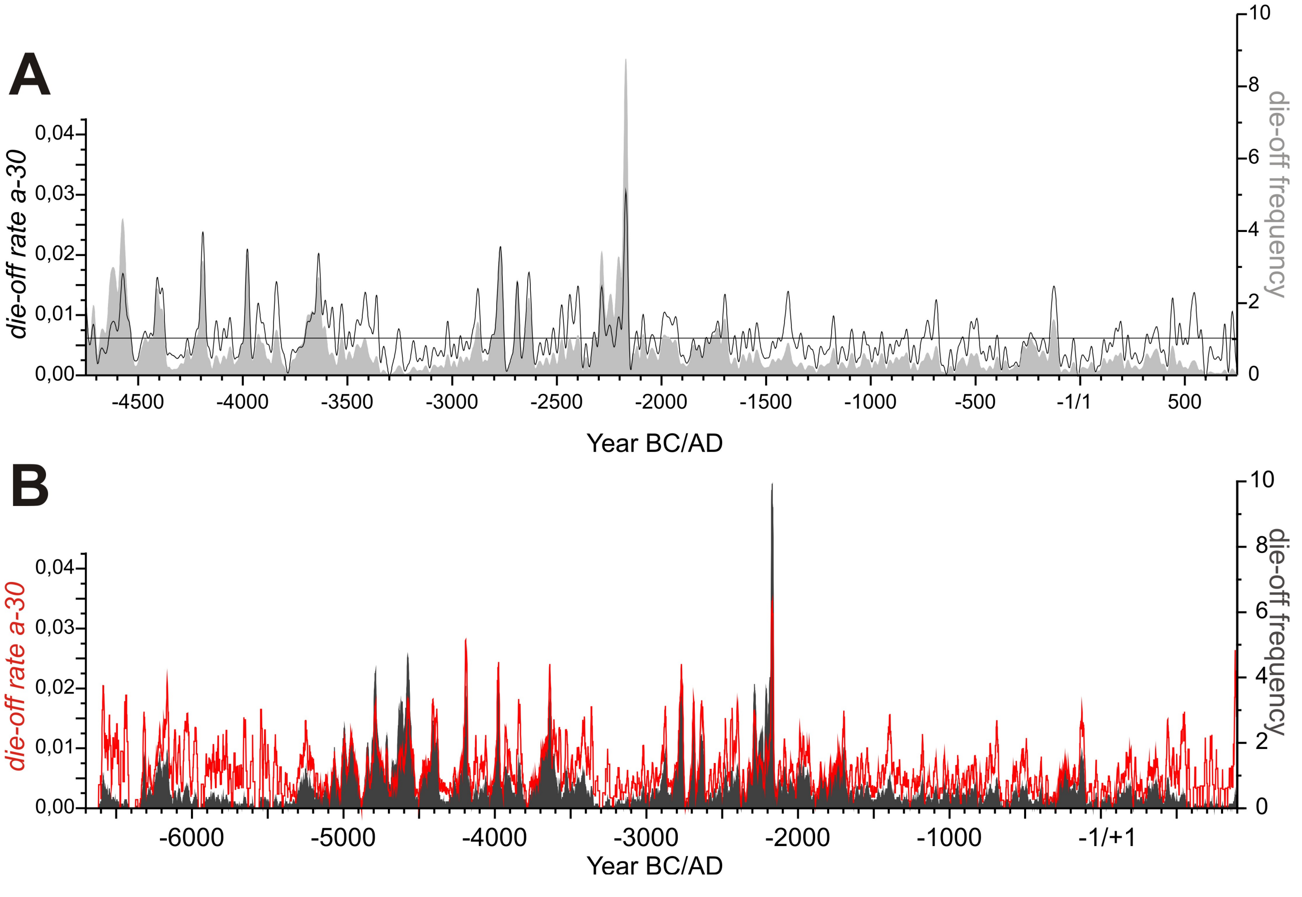

Figure 2: Die-off frequency (tree die-off /year) and *die-off rate a-30* for the combined data of oaks and pines from Northwest-German mires with dendrochronological dates (data end 2013, 2619 pine, 2090 oak, together 4700 trees). Curves smoothed by a 15-year running mean. **A:** For 4750 BC to 750 AD. **B:** For c. 6600 BC to 900 AD.

The chosen proxy, a quantification of tree die-off in proportion to the amount of potentially affected trees represented in the data set, can confidently be expected to depict water table rise where it occurs in represented stands. Naturally, where trees (of sufficient age for dendrochronological dating) are absent, hydrological change can not be detected by this method. This applies also to the later part of such phases, when the affected trees might already have died off. A continuous water table rise would thus elude the data. Hence, the proxy (die-off rate a-30) accounts for water table rise occurring nicely, but can, in turn, mostly not be used to determine the lack of water table rise.

The proxy served to give environmental background to the construction dates of wooden mire bridging trackways, all from the same region (Lower Saxony) and dated with equal precision i.e. by dendrochronology. It had been a subject of debate, whether these constructions were to be viewed as reactions to water table rise (e.g. Bauerochse 2003, Behre 2005, Brown and Baillie 1996, Metzler 2003). Investigations on the subject mostly relied on peat-stratigraphical data, either restricting the assessment to long-term climatic phases of several centuries in length (Plunkett et al. 2013), or retaining some uncertainty regarding the environmental change preceding or following the construction of a trackway (e.g. Bauerochse 2003, Metzler 2004). Relying on dendrochronological data alone made it possible to include more short-term events (hydrological changes of decadal scale) and, above all, improved the certainty of their actual temporal relation to the constructions. A majority of the included trackways was found contemporary to die-off phases. However, this does not necessarily imply a direct causality. For one, the link may be indirect, such as periods of crop failure caused by unfavourable weather leading to increased hostility among the human population and causing people to built retreat routes through the bogs or passages for their advancing military forces. Secondly, the observed coherence might also arise from the fast burial and thereby mostly good conservation of trackways from wet periods. This argument is only contradicted by the finding (manuscript 1), that the beginning of water table rise commonly preceded the trackway construction in the investigated cases.

Chronology extension

The DFG funded research project on peat-preserved pines this thesis is about (LE 1805/2-2) is the successor of the project (LE 1805/1-2) described in the thesis of Jan Eckstein (2009). From the work of Eckstein et al. (2009, 2010, 2011), a number of chronology segments had arisen, absolute dated on base of the pre-existant oak chronology. The work of Jan Eckstein with Dr. Hanns Hubert Leuschner closed with 1241 dendrochronological dated pines, covering 3598 years in five chronology segments {6483-5801 BC, 5606-3608 BC, 3034-2704 BC, 2432-2077 BC and 1399-1171 BC}. One aim of the continued research was to expand the cover of the pine chronology. In result, now (data end 2014) 3147 pines are calendar dated by dendrochronology, covering 5369 years in three segments {6703-5722 BC, 5606-3294 BC, 3238-1165 BC}. This is an addition of 1906 pines and 1771 chronology years, thereby closing two of the previously four gaps and reaching 220 years further into the past (Tables 1, 2 and 3, Figure 3).

Work on the Lower Saxony Bog Oak Chronology (LSBOC) was not in the focus of the study presented here. The oak chronology did play a role as a dating tool for the pines, and was also included in the study of an environmental signal (manuscript 1) and the description of the Göttingen tree ring archive (manuscript 2). Compared to the cover of the LSBOC described by Eckstein (2009) it has been extended though. This was not so much due to an addition of newly sampled oaks (only 68 new bog oak samples were taken), but rather the extended and well replicated pine chronology in turn served as a dating base for oak material. Thereby, the oak chronology was extended by 451 years, covering the time from 6628 BC to 6178 BC additional to its previous cover of 6069 BC to 928 AD.

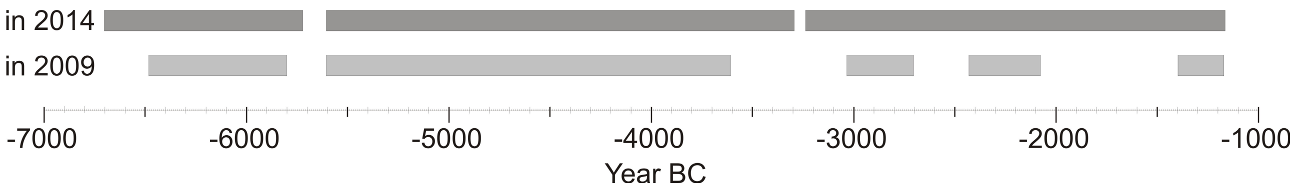

Figure 3: Cover of the pine chronology (LSBPC) by 2009 (described by Jan Eckstein 2009) and by 2014 (described here by Inke Achterberg).

Table 1: Pine chronology cover to date (end 2014).

	From	**To**	**Length [y]**	**Gap after [y]**
Segment 1	6703 BC	5722 BC	982	115
Segment 2	5606 BC	3294 BC	2313	55
Segment 3	3238 BC	1165 BC	2074	
Total			5369	170

Table 2: Addition to the pine chronology.

	Pine chronology establishment with participation J. Eckstein	Addition to pine chronology with participation I. Achterberg	Current state (2014)
Number of trees sampled	2397 pines	2881 pines added	5278 pines
Number of dated pines	1241 pines	1906 pines added	3147 pines
Years covered	3598 years	1771 years added	5369 years
Number of gaps	4 remaining	2 closed	2 remaining
Length of gaps (total)	1705 y remaining	1535 y covered	170 y remaining

Table 3: Location of mires and number of samples taken with participation of I. Achterberg.

Mire	Approx. location		Pines sampled (participation I.A.)
Nordmoor	~ 53,6 N	7,6 E	19
Vehnemoor	~ 53,1 N	8,0 E	48
Dümmer Basin {Vördener Moor, Venner Moor, Campemoor}	~ 52,4 N	8,2 E	163
Borsteler Moor	~ 52,6 N	9,0 E	521
Totes Moor	~ 52,5 N	9,4 E	842
Gifhorner Moor	~ 52,5 N	10,6 E	1190
Göldenitzer Moor	~ 54,0 N	12,3 E	98
Total			2881

Spatio-temporal reconstruction of raised bog development

An investigation of spatio-temporal raised bog development was carried out at site *TOMO_south* in the *Tote Moor* at lake *Steinhuder Meer* near Hanover. At that site, a large layer of in situ stumps exposed by peat mining contained trees from several millennia, including the oldest absolute dated pine trees in the data set. They originated from the fen-bog-transition, and therefore mark the time of raised bog growth at their respective location. The reconstruction is described in manuscript 3.

At the particularly interesting site, 477 trees were successfully dated, 210 of these true to their spot of growth, including 114 trees being in situ s.s.. These 210 tree stumps, together with two radiocarbon dated in situ stumps, were used for the reconstruction of raised bog development. Tree stumps that had been shifted by peat harvesting machinery were also included, if part of their root plate remained within the grown peat.

Unfortunately, a number of trees remained unsampled, and also a number of samples undated. The first being due to the great number of stumps at the site, and also to the condition of many of them, being long exposed and damaged by peat mining, making it hard to impossible to obtain usable samples from them. The latter was predominantly due to short tree-ring series, often delivering likely dates, but ring numbers being insufficient to make them reliable.

The trees preserved at the site generally had grown on fen peat and were overgrown by sphagnum peat, setting their death in context with the raised bog development and the related water table rise. The dense cover of the site with tree stumps and their distribution over four prehistoric millennia makes it a valuable object for investigation of mire development over time. Anthropogenic influence on the site can be assumed to have been neglectable, the time explored being prior to the third millennium BC.

The mapping of reconstructed bog expansion used a 'no trees after' approach, assigning an area to the last trees grown at the spot. Thereby, cases where bog development repeatedly killed a generation of trees, the spot remaining a marginal bog zone suitable to support large trees after the initial transition, where accounted for by their final change to tree-less raised bog site. Therefore, the reconstruction neglects trees from such marginal (repeatedly wooded) bog sites together with trees possibly preserved at flooded fen sites prior to raised bog development.

There have also been 56 peat stratigraphic corings at the site, 36 of which have also been measured for their elevation a.s.l. (trachyometrically for most, using a differential gps for a few conducted some years later). Their results show a rather homogeneous picture, suggesting a system ecologically stable over a long time, changing mostly by the location of the margin outlines.

In result, what clearly shows at this suitable, by comparison well-investigated site is the discontinuity of raised bog expansion. There clearly are times of pronounced progress, killing and preserving several trees in the process, and, in reverse, times of apparent stagnation or nearly such over longer periods (manuscript 3).

As climatic variation should play a relevant part in determining whether substantial bog expansion is taking place, this reconstruction is a contribution to the landscape and climate history of Northwest-Germany. Previously, bog core bases from northwest German mires had been radiocarbon dated by Pretzelberger et al. (1999), and the dendrochronological work of Eckstein et al. (2011) had dated a initial phase of raised bog development in the region to c. 7000 BC and a main phase of raised bog development to 5100-3600 BC. The study presented here (manuscript 3) shows the temporal pattern of the development between c. 6700 BC and 3400 BC in a case study.

Additional research

Göldenitzer Moor

Pine Tree stumps at a bog site outside of Lower Saxony have also been investigated. In *Göldenitzer Moor* near Rostock in Mecklenburg-Vorpommern 98 peat preserved pine stumps were sampled and documented. The pine stumps were extraordinarily well preserved. They were later processed and measured, but it has not been possible to cross date them dendrochronologically.

Taxus groove at Tote Moor

At a site in the northern part of the *Tote Moor* near Hanover, several yew trees (*Taxus baccata*) have been found. They were mostly stems of straight growth, some of them with roots. The Tote Moor has been inspected many times in different parts and investigated scientifically at a dozen sites, where numerous pine and oak trees were sampled. Yew trees were found at only one location within the large and well investigated mire. The occurrence of *Taxus* trees in German bogs is not unheard of (e.g. Brakhoff 1908, Hayen 1960), but far less common than that of *Pinus* and *Quercus* trees. The growth of *Taxus* trees within the mire appears to have been limited to one local occurrence. It has been possible to dendrochronologically cross date the yew tree samples amongst each other, but no valid match with the existing chronologies was obtained. The yew trees form a floating chronology of 343 years, compiled of 27 of the 29 sampled trees. This documents the *Taxus* occurrence to have been temporally as well as spatially limited. Over 100 pine and oak trees from the same site have been dendrochronologically dated, forming five temporal groups between c. 2500 BC to c.1180 BC. A transect of peat stratigraphic cores has been surveyed at the site. Furthermore, a core for palynological investigation was taken on the neighbouring platform of higher peat, which was left standing some 2-3 m above the level of the only in situ yew tree found. Pollen investigation in the frame of a student research project (FOLL – Forschungsorientiertes Lehren und Lernen) confirmed the temporal confines of *Taxus* occurrence only once in the covered period.

Perspective

The pine chronology still shows potential to be extended. This applies to the remaining gaps, as well as its reach further into the past and towards the present. This is supported by the existing radiocarbon-dated floating chronologies in these sections, and by the still large number of pine material available in the peat extraction areas of Lower Saxony (manuscript 2).

Further evaluation of the environmental, particularly climatic, indications in the dendrochronological data is desirable. Viewing dendrochronological records from several European regions together appears to be promising. Also detailed comparisons with other environmental records should be made.

Ecological study of the trees should continue, particularly regarding tree species distribution (of *Pinus*, *Quercus*, and *Taxus*) and its relation to the trophic level of the sites, but also with respect to the placing of the trees in the mire development, geological site characteristics and hydrological history.

Own contribution to manuscripts

Contribution to the compilation of the tree ring data (manuscripts 1-3)

The whole data set of northwest German (Lower Saxony) peat preserved pines is the base of all three manuscripts. Part of this data set was compiled previous to my own work by Jan Eckstein and Dr. Hanns Hubert Leuschner. More than half of its present extent was compiled by H. Leuschner and myself after that. To previously 2397 pines sampled by H. Leuschner and Jan Eckstein, 2881 pines were added by H. Leuschner and myself, adding up to 5278 at the end of my active participation. Jan Eckstein had closed his work with 1241 dendrochronologically dated pines, covering 3598 years. After that, 1906 pine trees were successfully dated, adding 1771 years to the chronology (table 2). In sampling, tree ring widths measurements and dendrochronological cross dating I have not worked alone but mostly together with H. Leuschner, and sometimes also student assistants. In fieldwork and sample processing, this is necessary anyway because of work security regarding the chain saw and circular saw. In cross dating, some dates were acquired by myself independently and confirmed by H. Leuschner's dating. Others were obtained together in a four eye method, or dated by H. Leuschner. My contribution to the compilation of the TRW data set included the following:

In preparation of fieldwork all maps containing previously sampled trees and their dates where available (via ArcGIS, using self-prepared tables) were produced entirely by myself, also assessing the numbers of samples already obtained from each potential sampling site. The packing of tools and materials for fieldwork was done by myself in large parts.

The sampling of trees via chain saw was done partly by myself. The documentation of find circumstances via photo, description protocol and GPS was done mostly by myself.

The processing and archiving of data (transfer of field protocols and visual data to digital tables; processing of GPS data and correct assignment into digital tables; naming and archiving photos) was done almost exclusively by myself. The compilation of fieldwork-documentation (in situ, state of decay, sampled tree part, root morphology, peat etc.), TRW-files (dates where obtained, number of rings measured, estimation of missing rings etc.), GPS data and elevation measurements where obtained, into one digital table was done exclusively by myself.

The processing of the samples (reduction; labelling; preparation and packaging and freezing; surface cut of radii) was done by myself in part (usually me being one of two people working together).

The measurement of TRW series was done by myself in part.

The dendrochronological cross dating was done partly by myself (as described above). The dating of the pine and oak chronologies from Northwest German mires is anchored to the present on base of chronologies made up of riverine oaks and archaeological/historical lumber, both of which I had no part in constructing.

The whole pine TRW data set was used for the manuscripts 1-3, as available at the respective times. For manuscripts 1 and 2 data of the oak chronology (LSBOC) is used additionally, which was compiled (almost entirely) before my participation. In manuscript 2 the chronologies of riverine and archaeological/historical wood are also referred to, which are no product of my work.

Contribution to manuscript preparation (manuscripts 1-3)

All manuscripts (manuscript 1-3) were written by myself. I have produced all maps (via ArcGIS and CoralDraw) myself. I have produced all curves and the underlying calculations myself (microsoft exel, Origin6.1, CoralDraw). I have produced all figures myself (via v-show, Origin6.1, CoralDraw), with figure 2 of manuscript 2 including the design for chronology cover taken from H. Leuschner. I took the photos myself, with exception of the one which is part of manuscript 2 figure 3 (taken by Jan Eckstein) and the sky view in manuscript 3 figure 8 (Sky view: ©2008 Google Earth, image ©2009GeoContent, ©2009 Tele Atlas.). All tables were prepared by myself.

Specific contribution to manuscript 1

Compilation of the tree data set as described above (see *contribution to the compilation of tree ring data*). For manuscript 1 the whole pine data set of Lower Saxony was used (Eckstein, J., Achterberg, I., Leuschner, H.) at the state it was at the time. The oak data set of Lower Saxony bog oaks (LSBOC), which was compiled by H. Leuschner mainly, was used additionally.
The manuscript and figures were prepared by myself (see *contribution to manuscript preparation*).

Archaeological literature in context of ancient trackways was compiled and evaluated by myself.
Literature regarding Holocene climate was compiled and evaluated by myself.
The dendrochronological data of trackways from literature and provided by DELAG (DEndrochronological LAboratory Göttingen) and the Lower Saxony State Service of Cultural Heritage was evaluated by myself. Dendrochronological dates that did not offer the desired precision, mostly due to decay of the outer wood, were excluded.

The development of the *die-off rate a-30* was done entirely by myself and on my own accord. It achieved to make die-off phases comparable, despite the large differences in replication of the dendrochronological record. The usage of die-off frequency (annual tree die-off) or mean age seemed inappropriate to me for the following reasons: The die-off frequency is directly affected by replication. Whether a given number of trees dying off within a certain length of time qualifies as a die-off phase greatly depends on the replication of the record. For example three of 200 trees dying off would not be an indicative event, while three of five trees dying of within short time might indicate some causal event. Mean age on the other hand is a comparable proxy. The problem of using mean age to detect die-off phases is the great influence of germination on the parameter. As rejuvenation does not represent the environmental signal relevant for this study, I refrained from using it.

To use the replication of the record 30 years previous to the year in question was the result of a try-and-error process with various methods of quantification. The time lack derives from the age the trees usually reach and the length of time a die-off phase commonly covers. It is aimed to represent an approximate total of trees which can die-off in a given die-off phase. It should therefore, at the time when the first trees die off, not be set before the germination dates of (too may) other trees of the same die-off phase. In turn, when the last trees of the phase die off, it should not be set (too far) within the die-off phase, when the number of trees was already reduced by the event.

In result, the timing of the die-off peaks was retained in comparison to the curve of raw die-off frequency. The height of the peaks was levelled, with regard to the number of trees represented in the data at the time.

The method to combine oak and pine records for the study was also developed by myself. As the records have some general differences, a pre-calculation combination of the two data sets into one appeared inappropriate. In general, pine replication is higher. This is partly due to the more costly (labour-intensive) dating of pine. Often, larger numbers of pine were required from one site, in order to obtain relative dated floating chronologies, which only then were successfully cross dated with the master chronologies. This is partly related to missing rings, which do not occur with oak. In part, the high replication of pine in certain periods is also due to intensely studied sites (Eckstein et al. 2010). However, due to ecological differences of the two tree species, they can sometimes represent different site conditions. The low replicated oak die-off phases have the same emphasis as those of the mostly higher replicated pine.

To give the records equal weight, die-off rate a-30 was first calculated for both species individually, and smoothed by a 15-year running mean. Where both species are represented, each was given 0.5 weight. Where one species was missing from the record, the other was given full weight.

Chi-square test was performed for various versions (e.g. regarding one construction year per trackway; the whole period of construction activity per trackway as individual years; the whole period of tackway construction with majority of years in or out of die-off phase; using different levels of smoothing the die-off curve; using running mean of different lengths for determination of average die-off; etc.). The outcome was significant in general, but due to the manifold possible variants of previous data-treatment, which would obviously influence the statistical analysis, I refrained from publishing a quantified correlation.

Specific contribution to manuscript 2

The dendrochronological data referred to was generated by myself in part (see *contribution to the compilation of tree ring data*). The manuscript and figures were prepared by myself (see *contribution to manuscript preparation*).

For manuscript 2 I performed wiggle matching of all (105) radiocarbon dates via *Oxcal* 4.2 online program (Bronk Ramsey et al. 2001, Bronk Ramsey 2009) on base of the IntCal13 calibration curve (Reimer et al. 3013).

Specific contribution to manuscript 3

The dendrochronological data referred to was generated by myself in part (see *contribution to the compilation of tree ring data*). The manuscript and figures were prepared by myself (see *contribution to manuscript preparation*).

For manuscript 3 I developed the approach for mire expansion reconstruction presented in the manuscript (last tree counts) and applied it to the site (manuscript 3, figure 5).

I generated tables suitable for further processing and interpolated the elevation of the mineral base on site *TOMO_south* via *ArcGIS* (manuscript 3, figure 6).

I classified the peat stratigraphy of 56 cores I took, mostly with assistance and supervision of B. Birkholz (manuscript 3, figure 8).

I dug under in situ trees investigating the root system (manuscript 3, figure 9).

References

Bauerochse, A., (2003): Environmental change and its influence on trackway construction and settlement in the south-west Dümmer area. In: Bauerochse, A., Haßmann, H. (Eds.): Peatlands – archaeological sites, archives of nature, nature conservation, wise use. 68-78; Rhaden/Westf.

Behre, K.-E. (2005): Die Einengung des neolithischen Lebensraumes in Nordwestdeutschland durch klimabedingte Faktoren: Meeresspiegelanstieg und großflächige Ausdehnung von Mooren. In: Gronenborn, D. (Eds.): Klimaveränderungen und Kulturwandel in neolithischen Gesellschaften Mitteleuropas, 6700-2200 v.Chr., RGZM-Tagungen 1, 209-220, Mainz.

Behre, K.-E. (2008): Landschaftsgeschichte Norddeutschlands- Umwelt und Siedlung von der Steinzeit bis zur Gegenwart. 308 p., Wachholtz Verlag Neumünster.

Brakenhoff, H. (1908): Der untergegangene Eibenhorst zu Ihorster Moor. Abhandlungen herausgegeben vom naturwissenschaftlichen Verein zu Bremen, v. 19, 276-279.

Eckstein, J. (2009): Dendroecological investigations on subfossil bog-pine forests in northwest Germany. PhD thesis at university of Göttingen.

Eckstein, J., Leuschner, H.H., Bauerochse, A., Sass-Klaassen, U. (2009): Subfossil bog-pine horizons document climate and ecosystem changes during the Mid- Holocene. Dendrochronologia 27, 129-146, 2009.

Eckstein, J., Leuschner, H.H., Giesecke, T., Schumilovskikh, L., Bauerochse, A. (2010): Dendroecological investigations at Venner Moor (northwest Germany) document climate-driven woodland dynamics and mire development in the period 2450–2050 BC. The Holocene 20 (2), 231-244.

Eckstein, J., Leuschner, H.H., Bauerochse, A. (2011): Mid-Holocene pine woodland phases and mire development – significance of dendrochronological data from subfossil trees from nortwest Germany. Journal of Vegetation Science 22, 781-794.

Ellenberg, H. (1996): Vegetation Mitteleuropas mit den Alpen. 1096 p., Ulmer Stuttgart.

Frohne, H. (1962): Pollenanalytische Untersuchungen im weißen Venn bei Verlen (Münsterland). Abhandlungen aus dem Landesmuseum für Naturkunde zu Münster in Westfalen, 24 (1), 1062.

Hayen, H. 1960: Vorkommen der Eibe in oldenburgischen Mooren. Oldenburger Jahrbuch 59 (2), 21-49.

Hughes P.D.M., K.E. Barber (2004): Contrasting pathway to ombrotrophy in three raised bogs in

Ireland and Cumbria, England. The Holocene 14 (1), 65-77.

Leuschner, H.H., Sass-Klaassen, U., Jansma, E., Baillie, M.G.L., Spurk, M. (2002): Subfossil European bog oaks: population dynamics and long-term growth depressions as indicators of changes in the Holocene hydro-regime and climate. The Holocene 12, 695–706.

Leuschner, H.H., Bauerochse, A., Metzler, A. (2007): Environmental change, bog history and human impact around 2900 B.C. in NW Germany – preliminary results from a dendroecological study of a sub-fossil pine woodland at Campemoor, Dümmer Basin. Vegetation History and Archaeobotany 16, 183-195.

Metzler, A. (2003): Early Neolithic peatland sites around lake Duemmer. In: Bauerochse, A., Haßmann, H. (Eds.): Peatlands. Archaeological sites, archives of nature, nature conservation, wise use. Proceedings of the Peatland Conference 2002 in Hannover, Germany. 62-67.

Metzler, A. (2004): Moorarchäologie in Niedersachsen. In: Fansa, M.; Both, F. (Eds.): Archäologie, Land, Niedersachsen: 25 Jahre Denkmalschutzgesetz – 400.000 Jahre Geschichte. Archäologische Mitteilungen aus Nordwestdeutschland, Beiheft 43; Landesmuseum Natur und Mensch Oldenburg, 471-475.

Overbeck, F. (1952): Das Große Moor bei Gifhorn – im Wechsel hygrokliner und xerokliner Phasen der nordwestdeutschen Hochmoorentwicklung. Niedersächsisches Amt für Landesplanung und Statistik, Veröffentlichungen Reihe A I, Band 41, Walter Dorn Verlag, Bremen-Horn.

Overbeck, F. (1975): Botanisch-geologische Moorkunde - unter besonderer Berücksichtigung der Moore Nordwestdeutschlands als Quellen zur Vegetations-, Klima- und Siedlungsgeschichte. Karl Wachtelholz Verlag Neumünster.

Petzelberger, Bianka E.M., Behre, Karl-Ernst, Geyh, Mebus A. (1999): Beginning and spread of raised bogs Northwest Germany – first results of a new project. Telma 29, 21-38.

Plunkett, G., Macdermott, C. Swindles, G.T., Brown, D. (2013): Environmental indifference? A critique of environmentally deterministic theories of peatland archaeological site construction in Ireland. Quaternary Science Reviews 61, 17-31.

Tahvanainen, T. (2011): Abrupt ombrotrophication of a boreal aapa mire triggered by hydrological disturbance in the catchment. Journal of Ecology 99, 404–415.

Von Bülow (1934): Die Bedeutung der Versumpfung für die Entstehung von Hochmooren in Deutschland. Geologische Rundschau, 277-284

Manuscript 1: IANSA Interdisciplinaria Achrchaeologica Natural Sciences in Archaeology, VI, 19-29

Contemporaneousness of trackway construction and environmental change: a dendrochronological study in Northwest-German mires

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Abstract

Tree rings provide not only a precise dating tool, they also contain information on environmental change. The well replicated tree ring record of Northwest-Germany therefore provides environmental implications with immanent absolute and precise dating from 6703 BC to 931 AD. This offers the opportunity to investigate the environmental context of archaeological finds, if they, too, are dated by dendrochronology. Here we investigate 13 peat-preseved trackways from the Northwest-German lowland with dendrochronological dating between 4629 BC (Neolithic) and 502 AD (Migration Period) for contemporaneousness with water table rise in the landscape. Such environmental change is well reflected in the eye-catching die-off phases of trees preserved in the mires. As environmental proxy, the parameter '*tree die-off rate a-30*' is introduced: The annual number of tree die-off events is divided by the number of live trees 30 years previously. In result, the majority of trackway constructions was found contemporaneous to mire water table rise and mire expansion. Possibly, water table rise was a motivation for trackway construction.

Key words

Wooden trackways, dendrochronology, mire, environmental change, Holocene climate, Neolithic

1. Introduction

The Northwest-German lowland changed in the millennia following the last glacial from a periglacial wasteland to a forest-wetland mosaic, where the expanding mires eventually covered about one third of the area (Behre 2008, Metzler 2006). While the North Sea successively claimed the land between Denmark and England, pushing ground water levels up and maritime conditions further south-east, people bridged the spreading mires by wooden trackways, evidently since the early neolithic (Metzler 2006). Finds of peat-preserved trackways are frequently reported for Northwest-Germany (e.g. Metzler 2006), and also from Ireland (Raftery 1996) and SW-England (Coles and Coles 1992). Whether their construction (Behre 2005, Metzler 2003), or possibly their preservation (Spurk et al. 2002), might be related to environmental changes and climatic fluctuations is debated (Bauerochse 2003, Baillie and Brown 1996). In Ireland, the occurrence of five 'lulls' in trackway construction activity between the Neolithic and modern Age was found to relate rather to cultural changes than to long-term hydrological variations (Plunkett et al. 2013). The present study however is focused rather on the precise alignment of individual constructions with mostly short (decadal) phases of water table rise in Northwest-Germany. Indications for increased humidity in trackway layers were repeatedly described, using pollen and peat analysis (e.g. Bauerochse 2003, Leuschner et al. 2007). Whether the constructions were actually contemporaneous to or following such environmental change is investigated in this study using dendrochronology. This provides precise dating for both, the trackway constructions and the mire water table rise. The latter is possible based on the large dendrochronological record of peat-preserved trees, originating from former mire (and mire-margin) woodland in the study area. The tree-ring record consists of 4700 trees, oak (*Quercus* spec.) and pine (*Pinus sylvestris*), from the mires of the Northwest-German lowland. The chronologies span from 6703 BC to 931 AD (at various stages described by e.g. Delorme 1983, Leuschner et al. 2002, Eckstein et al. 2011). The peat-preserved trees grew at sites strongly affected by hydrological change (e.g. Schweingruber 1993, Linderholm 2002, Eckstein 2009). The trees show phases of woodland establishment, growth and collapse (Eckstein et al. 2011). These phases show much synchrony across different sites in the study area (Eckstein et al. 2011), and also with the Netherlands, Ireland (Leuschner 2002) and Southern Sweden (Edvardsson 2011). They therefore qualify as indicator for environmental change in the region, which ought to be mostly climatically driven (Leuschner 2002). The phases of high tree mortality (die-off phases) have been identified to indicate mire expansion and mire water table rise. This was evident, i.a. on base of upward growing roots, the composition of peat forming plants and the degree of decomposition (Leuschner et al. 2002, 2007, Eckstein et al. 2009, 2010). Tree die-off phases are a good indicator for mire water table rise (Leuschner et al. 2002, 2007, Eckstein 2009, 2010), whereas tree-ring-width (TRW) has been found to reflect hydrological changes not exclusively at Central European mire sites (Dauskane et al. 2011). The meteorological implication of mire water table rise and mire expansion varies, but here, we focus on the timing of such landscape-level changes rather than their causes.

This study investigates a possible correlation of trackway construction with mire water table rise and mire expansion. In the following, dendrochronological dates for wooden trackways are evaluated for contemporaneity to die-off phases of the peat-preserved trees from the area.

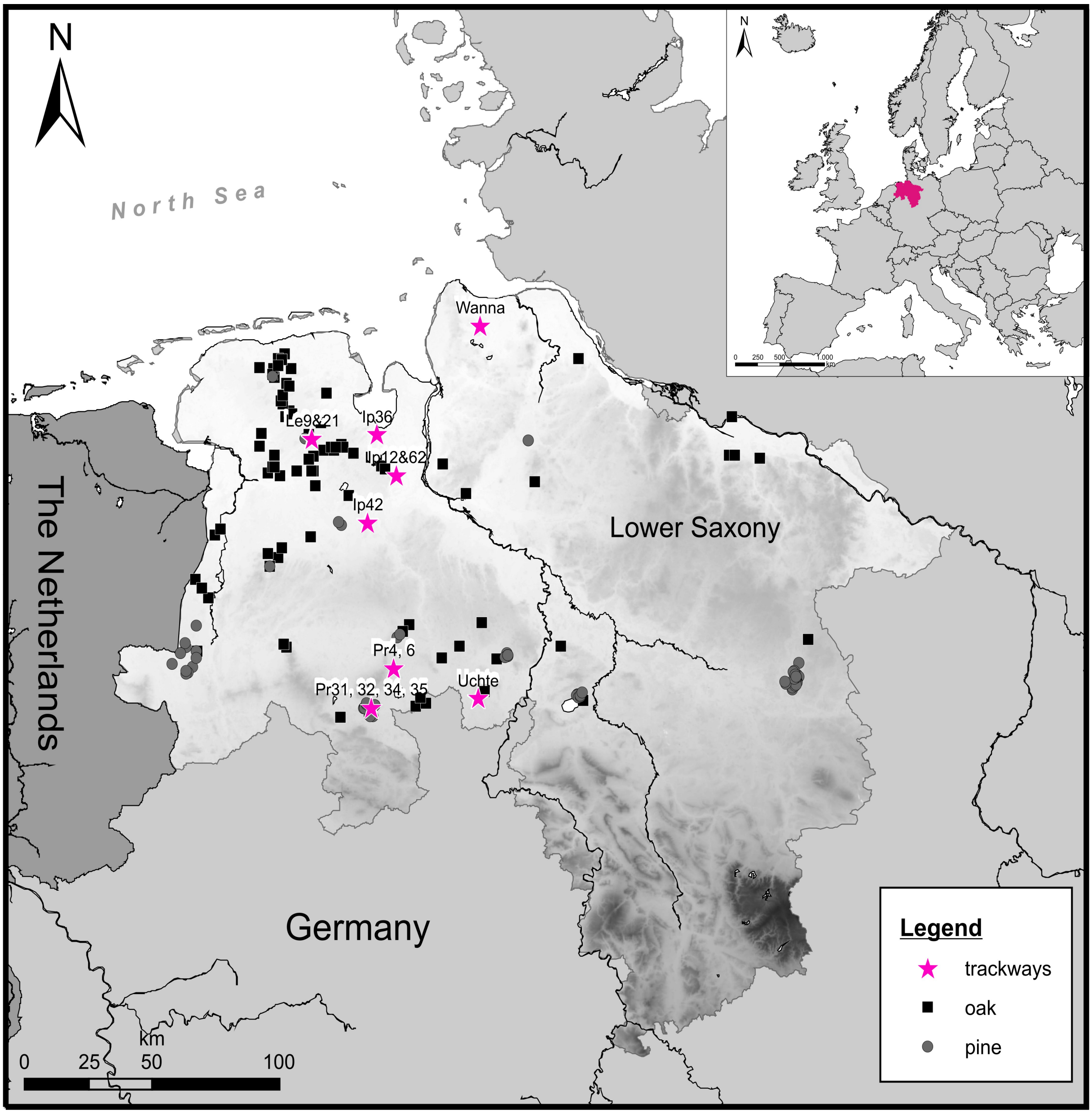

Figure 1. Study area in Northwest-Germany. Elevations are shaded and sampling sites indicated.

2. Material and Methods

2.1. The peat-preserved trees of Northwest-Germany

The tree species regarded in the following are oak (*Quercus* spec.) and pine (*Pinus sylvestris*) only. The woodland remains were preserved in peat, and mostly exposed by peat-harvesting. A total of 2090 oak and 2610 pine trees from Northwest-German mires, spanning from 6703 BC to 931 AD, form the environmental record. These are tree stumps and stems only, while no timbers from human constructions, like the trackways or buildings, are included in the environmental record.

The chronology of peat-preserved oaks cross-dates well with the Göttingen chronology of timbers from buildings and other constructions, which reaches back from present (2009 AD) to 610 BC. The main sections of both (oak and pine) chronologies of peat-preserved tree remains cross-date well with the Göttingen chronology of riverine oak from Central and North-West-Germany, which covers from 7197 BC to 1136 AD. All sections of the peat-preserved pine chronology are securely cross-dated with the peat-preserved oak chronology.

Generally, tree die-off reflects water table rise in the mires and mire expansion. These are related to hydrological changes, depending on sites. Ground-water levels relate to effective precipitation, and – at least in coastal areas – can be affected by sea level changes (Behre 2008). Trees from fen sites (minerogenic mires) are affected by ground water table fluctuation (Leuschner et al. 1986). In contrast, trees on raised bog sites (rain-fed mires) should mark dry phases (Moir 2010). Many of the trees were preserved at the base of raised bog peat, and therefore mark phases of raised bog expansion. Raised bogs function like sponges collecting rain water. Raised bog communities are highly competitive under nutrient-poor conditions in moist climates (Van Breemen 1995). Even though raised bog development is largely associated with high effective precipitation (Overbeck 1975), raised bog development atop fen peat can also be favoured by decreasing ground water tables (von Bülow 1935, Hughes 2004, Tahvanainen 2011). High precipitation results in accelerated peat-accumulation, which eventually disconnects the mire surface from the ground water (Overbeck 1975). Intermediate dry phases can also favour raised bog development on fen peat, by lowering the ground water table and thereby cutting the nutrient-supply to the surface (von Bülow 1935, Hughes 2004, Tahvanainen 2011). The fen-bog transition is often marked by tree layers, their die-off phases indicate the beginning raised bog growth.

The two tree species are represented unevenly at different sites. Generally, the more competitive oak dominates the nutrient-richer sites influenced by ground water. The oak material from such low-elevation sites displays long and dispersed die-off phases, caused by ground water level rise along an elevation gradient (Leuschner 2003). Fen sites at the transition to raised bog are rather levelled in elevation and water table. Hydrological changes at those sites cause distinct die-off phases in both species. The undemanding pine dominates only at poor sites. The occurrence of subfossil pines often marks the fen-bog-transition. The record also contains pines from sandy sites at the base of the peat and from raised-bog layers. The latter occur only occasionally and are most indicative of climatic variation (Moir 2010). Pine die-off phases are typically rather distinct, due to the more levelled character of the sites and to the sensitivity of trees growing close to their ecological limit.

Differences in wood preservation between the two species add to their disparity. The pines are mostly preserved to bark edge, which enhances the more distinct appearance of the pine die-off phases. In contrast, many of the oaks are preserved to the heartwood-sapwood boundary. Estimated numbers of missing rings were added for the die-off dates, but this naturally is less precise by comparison.

Tree die-off is a good indicator for the occurrence of mire water level rise in the study area. However, restrictions should be considered: firstly, drowning trees can take a few years to die, and therefore the die-off phase will be slightly lagging behind the beginning of water table rise. Secondly, the absence and the end of die-off phases are somewhat less reliable indicators. This is due to the detection of water level rise by this method requiring sufficiently old trees at affected sites, which can at times be absent or already dead.

2.2. The trackways

Over 300 peat-preserved trackways have been reported for the region (Metzler 2006), but precise (i.e. dendrochronological) dates for them are scarce. The dendrochronological trackway-dates from the study area include dates taken from literature, as well as age determinations performed in the dendrochronological laboratories of Göttingen (indicated in Table 1). The number of dendrochronological dates for peat-preserved wooden trackways is relatively low, due to the early excavation of the trackways since the 19th century, when dendrochronological dating was not sufficiently established and the long tree-ring-chronologies had not yet been developed. The trackways that are included, vary greatly in number of dated timbers, preservation state of the wood and documentation. Therefore, detailed evaluations (i.e. the time-span of usage etc.) were not possible in most cases. Trackways without certain and precise determination of at least one felling date were excluded.

The study includes 12 (+1) trackways (Table 1). The Northwest-German trackway finds have archaeological IDs (indicating the location or first investigator). Two of the trackways included in this study have no IDs to our knowledge, and are designated by their place of origin (i.e. *Wanna* and *Uchte*). In some cases, two trackways excavated at different times, turned out later to be parts of one trackway, interrupted by mineral soil islands in the mire. Their sections have been united for this study, using both original trackway-IDs (i.e. *Ip12&Ip62* and *Le9&Le21*). In reverse, one trackway appeared in dendrochronological investigation to contain timbers from a predecessor construction (Schmidt 1992). This construction previous to *Ip12* is called *Ip12a* in the following. Also, simultaneous constructions occur. This study has a temporal focus, and therefore **11 construction dates** are referred to, rather than 12 (+1) trackways (Table 1).

Table 1: The dendrochronologically dated trackways of the Northwest-German lowland. Dates regarding last measured ring. [1]: dated by B. Leuschner, DELAG, [2]: dated by B. Schmidt.

Construction date no	Construction date	Trackway ID	Timber dates	Bog Area	Published i.a.
1	4629- 4545 BC	*Pr31*	4628- 4545 BC[1]	Campemoor	Bauerochse et al. 2012
2	3798 BC	*Pr35*	3798 BC[1]	Campemoor	Bauerochse et al. 2012
3	3701 BC	*Pr34*	3701 BC[1]	Campemoor	Bauerochse et al. 2012
4	2900-2882 BC	*Pr32*	2900-2882 BC[1]	Campemoor	Leuschner et al. 2007
5	1357 BC	*Wanna*	1357 BC[1]	b. Wanna	unpublished
		Ip36 / Pr36	1357 BC[2]	Ipwegermoor	Schmidt 1992
6	754-749 BC	*Ip12a*	754-749 BC[2]	Ipwegermoor	Schmidt 1992
7	719-713 BC -682 BC	*Le21*	719-718 BC[2] , 683/682 BC[2]	Lengener Moor	Schmidt 1992
		Le9	717-714 BC[2]	Lengener Moor	Schmidt 1992
		Ip12	716-713 BC[1,2]	b. Oldenburg	Schmidt 1992
		Ip62		b. Oldenburg	
8	128 BC	*Ip42*	128 BC[1]	Wittemoor	Metzler 2006
9	60 - 43 BC	*Pr6*	60-55 BC, 43 BC 53-46 BC[1,2]	Großes Moor b. Diepholz	Fansa & Schneider 1996
10	222 AD	*Pr4*	222 AD[1,2]	Großes Moor b. Diepholz	Fansa & Schneider 1996
11	497 – 502 AD	*Uchte*	497 – 502 AD[1]	Uchter Moor	unpublished

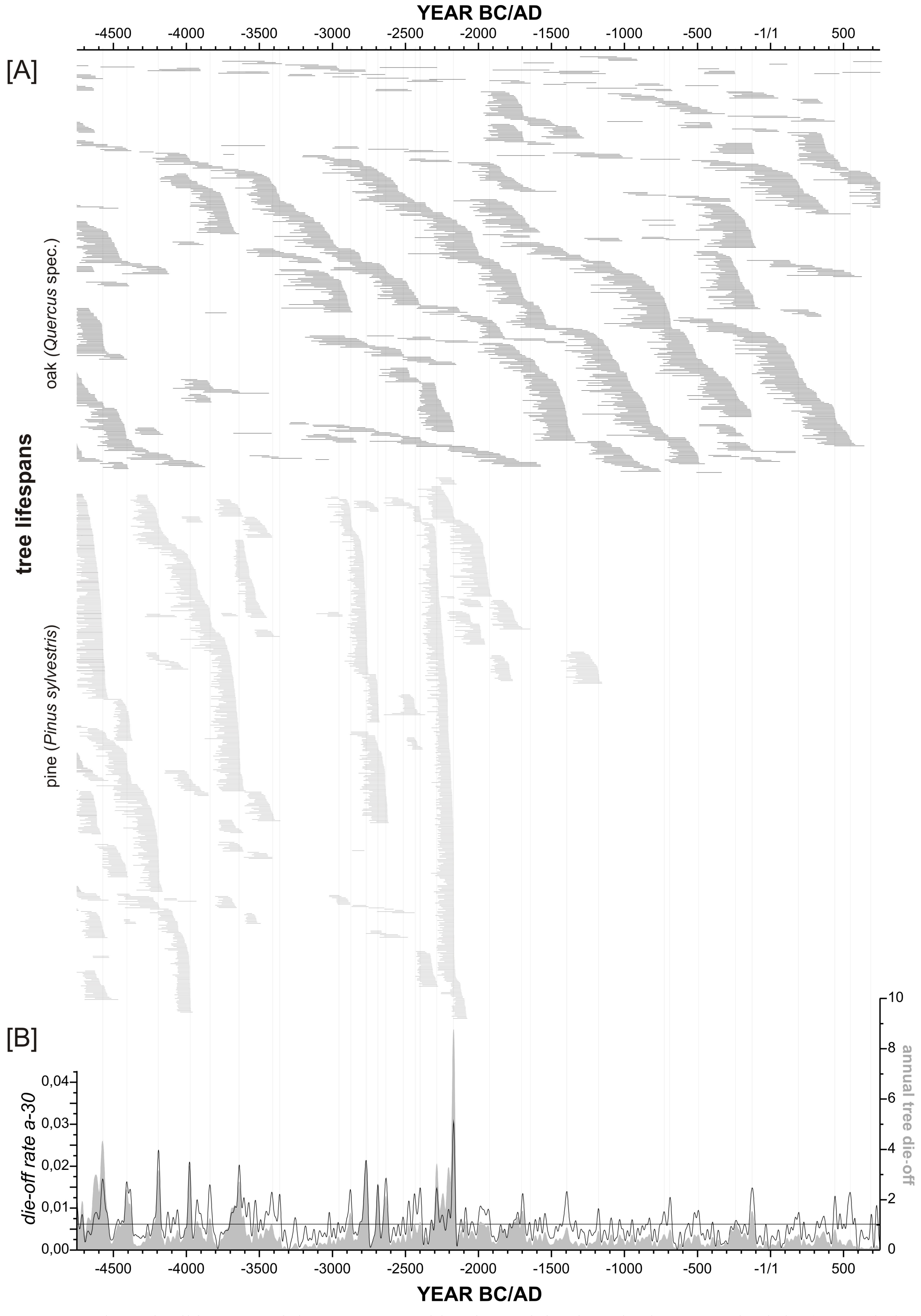

Figure 2. [A] gives the lifespans of the trees, sorted by time of death and mire area of origin (several sites taken together). Severe die-off events are indicated by vertical lines (grey).
[B] gives the annual tree die-off (grey filled, scale on the left), and the corresponding *die-off rate a-30* (black line, scale on the right). Both are smoothed by a 15 year FFT. The mean value of the *die-off rate a-30* is indicated by a horizontal line.

Excluded trackways

Five dendrochronologically dated trackways were excluded, because erosion and decay on the outer part of the timbers did not allow for precise determination of felling dates. The 'dates after which' for these trackways are: Bc34, after 763BC and after 752 BC; Pr3, after c.665-640 BC; Pr25, after 218-160 BC; Bc32, after 85 AD and after 120 AD; Cl01, after 273 AD and after 334 AD.

2.3. Method: die-off rate a-30

As described in 1., the peat-preserved trees from the area display synchronous phases of tree-establishment and common die-off. Particularly the die-off phases are highly indicative of hydrological change (water table rise and mire expansion). However, the heterogeneous replication and overlapping woodland phases in the record do not allow for a good determination of die-off phases via die-off frequency, replication or die-off percentage.

Therefore, the ***die-off rate a-30*** was developed, i.e. annual tree die-off divided by replication 30 years previously. The time lag of 30 years was chosen, according to the common length of tree generations and die-off phases in the data-set. This reduced the replication-dependency of die-off peak- height, while retaining the temporal distribution of the die-off phases (Figure 2).

Oak and pine have been combined in the *die-off rate a-30* displayed in Figure 2, and are displayed separately in Figure 3. A separation by species is advantageous, as the environmental signal of both species is not entirely identical, due to ecological differences.

The estimated number of rings missing to bark was regarded for the die-off dates. A reduced data-set was tested, in which all samples with a standard deviation of missing rings to bark larger than 3 (eroded samples) were excluded. This produced no notable alteration of the curve. As mentioned above, the vast majority of pines are preserved to bark edge. The oaks mostly feature sapwood, which allows for good estimations, and in several cases sapwood-rings could not be measured, but counted.

To show the relation between die-off frequency and the *die-off rate a-30*, dates of all trees are shown and used to calculate the *die-off rate a-30* in Figure 2. But because pine is clustered in the record in large numbers, their signal swallows up that of oak, which had not been sampled in the same fashion. To retain the environmental signal as best as possible, the *tree-die-off rate a-30* used in the following was calculated differently: *die-off rate a-30* was calculated for each species, and smoothed by a 15-year running mean (Figure 3). These oak and pine values were averaged to gain the *tree die-off rate a-30* (Figure 3). Where one species featured 0-values due to 0 replication, the values of the other species were used alone. The mean value is calculated from the *tree die-off rate a-30* over the 5500 years shown.

3. Results

The main result of this study is, that the majority of investigated trackways were found contemporaneous to tree die-off phases (3.2., Figure 3), which indicate water table rise and mire expansion (see 1. and 2.1.). The die-off phases are displayed in this study by the *die-off rate a-30* (3.1., Figure 2 and Figure 3). One case of contemporaneousness of trackway construction and tree die-off phase (trackway *Pr 31*, 4629 - 4545 BC) is described more detailed (3.3., Figure 4).

3.1. Die-off phases

The *tree die-off rate a-30* features over-average values (regarded as die-off phases) for 40,4% of the 5500 years regarded. There are two cases of an edge-effect, where a small number of die-offs are over emphasised by the rate. This is the case around 3360 BC and around 1645 BC, where 'last survivors' cover the edge of pine-chronology gaps for decades (Figure 2 and Figure 3). With this exception, the *die-off rate a-30* reflects the tree distribution very well.

The two tree species show much agreement, but also differences in their die-off curves (Figure 3). In general, the pine die-off phases are shorter and more distinct than those of the oaks (see Figure 2a and Figure 3a, compare 2.1.).

In the regarded time, from 4750 BC to 750 AD, the distribution and appearance of die-off phases varies over time as well:

The period before c. 3500 BC is well represented by both tree species. Pine and oak both show distinct and synchronous die-off phases (Figure 3a). High and distinct peaks occur approximately every 150-250 years. The die-off phases are largely related to the initiation of raised bog growth at the respective sites.

Between c. 3500 BC and c. 1500 BC, the pine record produces prominent peaks, which mark raised bog expansion at inland sites, around 2880 BC, 2740 BC, 2280 BC and 2175 BC. The contemporary oaks mainly stem from low elevation sites, influenced by groundwater. Their die-off phases appear more moderate and long stretched, as the trees die subsequently along an elevation gradient. An example for disagreement between the species is the pine-only die-off peak around 2740 BC.

After c. 1500 BC, there are only few dated pines. The oak material in this section originates from inland raised bogs, where they mark the fen-bog transition. Similar to the first section (before c. 3500 BC), these die-off phases appear more distinct. The oak peaks around 700 BC, 550 BC and around 120 BC appear particularly clear.

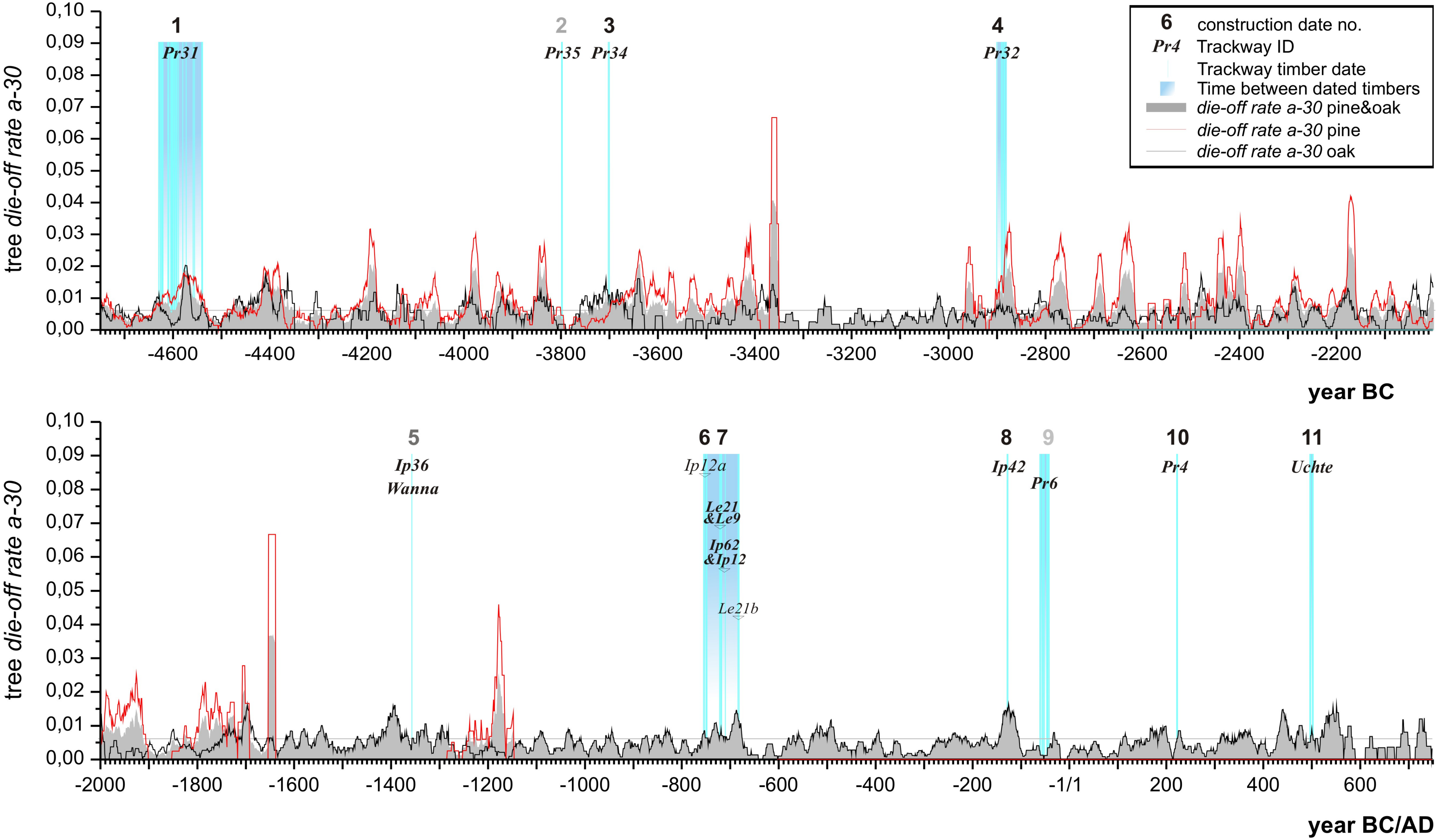

Figure 3: The *die-off rate a-30* is displayed for oaks (black), pines (red), smoothed by a 15-year running mean. The *tree die-off rate a-30* (average of the other two curves) is shown (grey, filled) with its mean value (grey horizontal line). The trackway timber dates are indicated by vertical lines (blue), with coloured boxes uniting dates from one find. The construction date numbers are given above, in grey for construction dates outside of die-off phases. The trackway-IDs are given below the date numbers.

3.2. Contemporaneity of trackway construction and die-off phases of the peat-preserved trees

Nine of eleven trackway construction dates (81%) date clearly within die-off phases (Figure 3). Some of them are represented by more than one trackway. However, at one of these dates (date 5), the *tree die-off rate a-30* shows values only slightly above average.

Two trackway construction dates are contemporaneous to below average *die-off rate a-30* values. One of these, date 2, 3798 BC, dates directly (three years) after a die-off phase, and therefore appears in context with environmental change nonetheless. On the contrary, the trackway construction date 10 shows no apparent temporal relation to tree die-off phases. It dates to a period in which the tree record is represented by oak only.

3.3. Trackway Pr31, documented for 4629 - 4545 BC (Figure 4)

Tree die-off is a sound hydrological indicator, but by no means the only environmental indicator contained in the dendrochronological record. In the following, tree-ring-width (TRW) variability is additionally considered for one trackway construction date. The Neolithic trackway *Pr31* (date 1, 4629 – after 4545 BC) is the oldest construction in our data. It is represented by a number of dated timbers, with a range of dates accounting for repeated work on the trackway (Figure 4a). The contemporaneous dendrochronological record is well replicated for both tree species. Pine and oak from several sites display a major die-off phase at the time (see Figure 3a and Figure 4c). Stratigraphically, the oaks as well as the pines largely mark the beginning of raised bog growth at respective sites. Conditions stressful to the trees are also implied by a contemporaneous series of growth depressions displayed by the regional TRW-Chronologies (Figure 4b, grey boxes).

Samples of 36 timbers from two excavated sections of trackway *Pr31* were dated. They display a range of dates, dispersed over 84 years. A number of samples preserved to bark edge, accompanied by other samples that date shortly prior to these, indicate construction and maintenance for 4629 BC, 4614 BC, 4606 BC, 4590 BC, 4557 BC and after 4545 BC (dates regarding last ring, Figure 4a).

The contemporaneous die-off phase appears long-stretched with three peaks (Figure 2a). It is reflected by both tree species likewise, with some minor differences (Figure 4c).

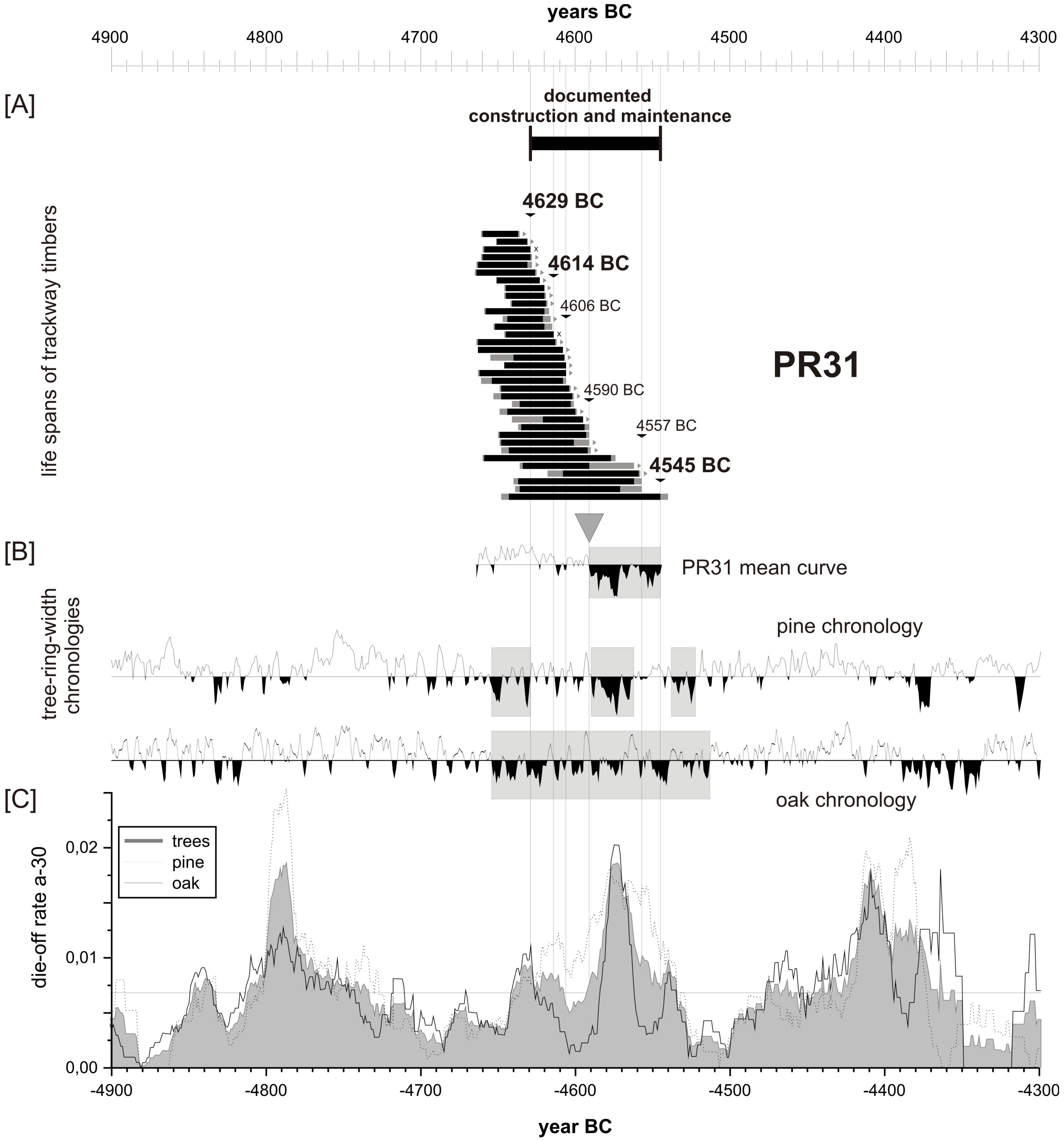

Figure 4. [A] shows the life spans of the trackway timbers from *Pr31*. Measured rings in black, missing rings are indicated in grey. Grey arrows indicate where more rings may be missing. Timbers with sure bark edge are indicated with 'x'. Clustering dates, sure felling dates and the last acquired date are indicated by vertical lines and labelled.
[B] shows the TRW-mean curve of the measured trackway timbers, the Northwest-German pine and oak TRW-chronologies. The year 4590 BC is indicated by a triangle. It is the beginning of the growth depression displayed by the trackway timbers and also the begin of a growth depression displayed by the pine and oak master chronologies, as well as a apparent maintenance date, indicated by a cluster of trackway timber dates.
[C] gives the *die-off rate a-30* for the trees (average of the 15-year running mean *die-off rate a-30* curves for pine and oak) and its mean value (horizontal line).

The supposed first construction (4629 BC) is contemporaneous to a first die-off pulse of the die-off phase (Figure 4c). Maintenance appears to have taken place rather continuously, as dates scatter over the following years. The maintenance activity of 4590 BC displays the most striking concurrence: in 4590 BC, increased stress is reflected by drastic declines in the oak and pine TRW-chronologies (Figure 4b). Also, the TRW- mean curve of the trackway timbers, representing a local signal, displays a sharp decline in ring width. After 4590 BC, work on the trackway seems to halt, as only two, not fully preserved, timbers date within the following 30 years. This apparent maintenance-halt is contemporaneous to the main peaks of the die-off phase (Figure 4c, also Figure 2a), and also to pronounced growth depressions in all three TRW-chronologies (Figure 4b). Shortly after both tree species have passed their main die-off peaks, the next maintenance activity is apparent, in 4557 BC. The last peak of the die-off phase occurs around 4540 BC for pine and oak, around the same time as the last date acquired from the trackway (4545 BC with 5+-5 missing rings). This makes the time of documented work on the trackway practically identical with the duration of the die-off phase. Strikingly, construction, maintenance pause and abandonment all appear to coincide with die-off-peaks. The maintenance activity in 4590 BC is contemporaneous to a strong negative growth reaction of the trees and the rise of the die-off-curves toward the main peak.

4. Discussion

4.1. General

This comparison shows a considerable temporal agreement of trackway construction with tree die-off phases: Nine of eleven trackway construction dates, corresponding to ten of twelve trackways (plus a supposed predecessor construction), date clearly within tree die-off phases. One construction date follows a die-off phase by three years.

Indications for wet phases in context with trackway finds have repeatedly been described (e.g. Bauerochse 2003, Behre 2005). Whether these wet phases were actually contemporaneous to the time of construction, is now clarified by means of dendrochronological dating for both, trackway constructions and water table rise.

What remains subject for discussion, is the reason for the observed correlation. There are two possible explanations: firstly, the correlation might be due to better preservation of trackways from wet periods (Spurk et al. 2002). Secondly, water table rise and mire expansion might have motivated trackway construction (Bauerochse 2003, Bauerochse et al. 2012, Behre 2005, Leuschner et al. 2007, Metzler 2003).

A preservation-produced correlation of wet phases and trackways would be expected to depict trackway constructions preceding water table rise. The here presented data indicates the opposite is the case, showing constructions following water table rise. This does not point towards a conservatory bias, but rather towards environmental change influencing construction activity. Conservation conditions in the mires were generally good over long periods. This is indicated by thick continuous layers of weakly decomposed peat and well preserved ancient wood, found just below mire surface. This is particularly true for the nutrient poor and acid raised bogs. However, preservation of organic material is generally better with increasing wetness, and well preserved timbers are vital for this study. Spurk et al. (2002) took the preservation of ancient trackways for an indication of wet conditions in itself. Well preserved constructions are more likely to be found, excavated and dated. In the study area, over 300 trackways were described (Metzler 2006), though, and the relatively small number of dendrochronological age determinations for them is mostly due to their early excavation, before dendrochronological dating had been sufficiently established. Decay and erosion on trackway timbers can often be assigned to the time after mire drainage. Nonetheless, an impact of varying conservation conditions cannot be ruled out entirely, until more dated trackways are available for comparison. Should varying preservation conditions be the cause of the observed correlation, this restriction should be taken into account when archaeological wetland-finds are being interpreted.

Hydrological change on landscape-level surely affected the human population, in their land use, mobility, economics and social stability. Environmental changes and socio-cultural dynamics are intertwined in multiple ways (Gronenborn 2006). So there might be indirect connections between environmental changes and construction activity, as crop failure can cause people to change their behaviour or location.

But what of a more direct effect of environmental forcing on trackway building activity? The context of increased surface wetness had repeatedly been suggested for excavated trackways, mostly based on peat-stratigraphical and palynological indications (i.a. Bauerochse 2003, Behre 2005, Baillie and Brown 1996, Leuschner et al. 2002, 2007, Metzler 2003). Several authors saw the motivation for the construction of trackways in such environmental change (e.g. Bauerochse 2003, Behre 2005, Leuschner et al. 2007, Metzler 2003).

On the British Isles trackway construction clusters were observed (e.g. Baillie and Brown 1996, Brunning and Macdermott 2013). Plunkett et al. (2013) have compared these temporal clusters to testate amoebae records from peat as a proxy for mire surface wetness. They see no clear relation of trackway clusters in Ireland with hydrological change. In contrast, in the UK, Brunning and Macdermott (2013) find these clusters to correlate well with phases of wetter climate, indicated by peaks of ice raft debris in the Atlantic and atmospheric carbon isotopes. However, in both cases clusters which span several centuries are considered together with long term environmental changes, whereas the present study focuses on the actual timing of individual constructions and their contemporaneousness with short-term environmental changes. We agree, however, with Plunkett at al. (2013), that motivation for trackway construction in general is surely not monocausal.

The trackways were constructed very differently, some are narrow bridges, others firm wooden roads fit for wheeled traffic. Mire development should have affected all of them (Raftery 1996), e.g. by drowning of older trackways, impassability of previously walkable mires, or blockage of formerly dry routes due to paludification and mire expansion.

The previous statement, that the wetlands in question were generally wet enough to provide good preservation over several millennia, does not necessarily mean, that they were always too wet to walk on. Of course, passability is relative, depending on the required frequency and convenience of passage. However, the observation of numerous short trackways bridging the lagg (wet fen at raised bog margin) towards raised bogs on the British Islands (Brunning and Macdermott 2013) supports the view, that prehistoric people did not always require trackways to walk on raised bogs. To relate the trackway occurrence in raised bog to humid phases, which might have affected mobility directly is therefore obvious.

4.2. Site specific comparisons

Trackway construction date 1 (4629-4545 BC, *Pr31*) is a striking example of close temporal agreement between the environmental parameter and work on the trackway. The first construction dates contemporaneous to the first steep rise of the tree die-off curve, the last timber date is contemporaneous to the final peak of the die-off phase. Within the over 80 years in which the trackway had been maintained, there is a 30 year activity gap, which is contemporaneous to the main peaks of tree die-off. A possible explanation for the gap is a temporary flooding of the trackway or its surroundings, causing intermediate abandonment. Likewise, the construction, as well as the final abandonment or the trackway appear related to water table rise.

Construction date 2 (3798 BC, *Pr35*), dates three years *after* a die-off event, displayed most clearly by pine. At that time, the Northwest-German oak chronology displays a distinct growth depression, which also commonly corresponds to increased surface wetness at the mire stands. The considerable water table rise at the site, which had been observed in palynological data (Bauerochse 2003) on the other hand, probably corresponds to the major die-off phase which begins some 40 years after the construction of Pr35, and is contemporary to date 3 (3701 BC, *Pr34*) instead.

Interestingly, the South-English S*weet Track* had been constructed nine years previous to trackway *Pr35*. For that site (Somerset Levels, UK), indications for water level rise were observed between the constructions of the *Post Track* in 3838 BC and the *Sweet Track* in 3807 BC (Brunning and Macdermott 2013). Even though the sweet track is located c. 700 km from the German site, climatic variations can be in tune. This is apparent in the far going agreement that has been observed between the oak chronologies of Northwest-Germany, the Netherlands and Ireland (Leuschner et al. 2002), including the regarded time around c. 3800 BC. As Southern England is located between Ireland and Northwest-Germany, a similar development there at the time seems likely. Hence, the construction of *Pr35* appears to stand in context of a preceding mire water table rise, which seems to have been caused by climatic conditions in the wider region.

Construction date 4 (c. 2900-2883 BC, *Pr32*) is another example of suggestive contemporaneities. It was found to have been constructed as well as abandoned in context of mire water table rise, uniquely recorded by on-site trees (Leuschner 2007).

In case of trackway construction date 5 (1357 BC, *Wanna* and *Ip36*) the contemporary tree-record is oak-only. The *tree die-off rate a-30* is only slightly over-average, making this a borderline-case. It has a low replication, as it is typical for moist periods. At a low-elevation site near the coast, which had long been forested, the last trees died off shortly before. An inland-site records contemporaneous fen-bog-transition at the start of the die-off phase. Both point towards wetness. Most remarkable is the contemporaneous construction of two trackways in the same year, some 70 km apart from another.
Interesting is also a find from the adjacent region: Dendrochronological dating of Bronze Age Tree-Trunk Coffins from the Jutland Peninsula (Denmark and N-Germany) revealed, that their vast majority (25 of 28 dated coffins) had been made within only fifty years, between 1391 and 1344 BC (Christensen at al. 2007). While the burial custom lasted over a millennium, most of the thousands of burial mounds in the region did not contain preserved coffins (Christensen at al. 2007). Whether more humid conditions in the mid-14th century BC might have favoured the preservation of the coffins, which were not peat-embedded, is uncertain.

Water table rise at the time of construction dates 6-7 (date 6, 754-749 BC, *Ip12a*; date 7, 719-713 BC and 682 BC, *Le9&Le21* and *Ip62&Ip12*) is clearly evident and observed at other sites in Europe. Most prominently, the abandonment of the dwelling at Biskupin (Poland) has been connected to water table rise and dated dendrochronologically to 721 BC (Waszny 1994). Tree ring records display the event at c.720 BC in Ireland as a germination phase, in the Netherlands as a die-off phase and in the German trees as germination and a die-off phase, with simultaneous growth depressions in either data set (Leuschner et al. 2002). Furthermore, the Dutch subfossil oaks from *Diemen* display a gap in germination events between 880 BC and 670 BC, also attributed to this event (van Geel at al. 2009).

Moreover, paleo-environmental records from peat and pollen data record a significant wet-shift across Britain and central-Europe and elsewhere (van Geel et al. 1996). It has been ascribed to the time in question, e.g. by radiocarbon dates c. 800-650 BC for Jutland recurrence surfaces (Barber et al. 2004). Particularly the pollen records leave no doubt as to the nature and severity of the event, however, options of precise alignment are limited, as peat layers are, by comparison, not well datable, and their formation can be a very slow and/or time-lagged process (Blackford 2000).

The trackways (754-682 BC) were clearly constructed in a time of environmental change, which appears to have been a time of socio-cultural changes as well. Migration to the coastal marsh and other low elevation sites (c. 2 m a.s.l.) of the Northwest-German lowland (Schwartz 1990) and the adjacent NE-Netherlands (e.g. Waterbolk 1962) dates around this period. Connections with hydrological and coastal changes (van Geel 1996) or land-use caused erosion and dune formation on the Geest plateau (Waterbolk 1962) have been suggested.

The trackways of date 6-7 are kilometres long, elaborately built and broad constructions of massive oak split-planks, which appear fit for wheeled traffic and hence might have been part of a long-distance connection. The Bronze Age - Iron Age transition was accompanied by the collapse and establishment of trade-route systems (Collis 2003), which might have had some effect on road building activity here. And then again, socio-cultural dynamics can be linked to environmental change in turn (e.g. Groneborn 2006).

5. Conclusion

The tree die-off phases in the mires of the area are reflected well by the *die-off rate a-30*. This parameter was designed to show variations within years and decades rather than long-term changes. The precisely (dendrochronological) dated tree die-off phases indicate water table rise and mire expansion. The study found, that the majority of dendrochronological trackway construction dates from the study area are contemporaneous to die-off phases of peat preserved trees. If this is not an effect of conservation, the finding supports the view, that, beside sociocultural aspects, the timing of trackway construction might commonly have been related to mire expansion and mire water table rise.

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References

Baillie, M.G.L., Brown, D.M. (1996): Dendrochronology of Irish bog trackways. In: Raftery, B. (Ed.): Trackway excavations in the Mountdillon bogs. Irish archaeological wetland unit 1996.

Barber, K., Chambers, F., Maddy, D. (2004):: Late Holocene climatic history of northern Germany and Denmark: peat macrofossil investigations at Dosenmoor, Schleswig-Holstein, and Svanemose, Jutland. Boreas, Vol. 33, pp. 132–144.

Bauerochse, A. (2003): Environmental change and its influence on trackway construction and settlement in the south-west Dümmer area. In: Bauerochse, A., Haßmann, H. (Eds.): Peatlands – archaeological sites, archives of nature, nature conservation, wise use. 68-78; Rhaden/Westf.

Bauerochse, A., Leuschner, H.H., Metzler, A., (2012): Das Campemoor im Neolithikum. Jahrbuch für das Oldenburger Münsterland 2012, 61. Jahrgang, Heimatbund für das Oldenburger Münsterland, 135-153.

Behre, K.-E. (2005): Die Einengung des neolithischen Lebensraumes in Nordwestdeutschland durch klimabedingte Faktoren: Meeresspiegelanstieg und großflächige Ausdehnung von Mooren. In: Gronenborn, D. (Eds.): Klimaveränderungen und Kulturwandel in neolithischen Gesellschaften Mitteleuropas, 6700-2200 v.Chr.. RGZM-Tagungen 1, 209-220.

Behre, K.-E. (2008): Landschaftsgeschichte Norddeutschlands- Umwelt und Siedlung von der Steinzeit bis zur Gegenwart. 308 S., Wachholtz Verlag Neumünster 2008.

Blackford, J. (2000): Paleoclimatic records from peat bogs. Tree 15 (5), 193-198.

Brunning, R., Macdermott, C. (2013): Trackways and roads across the wetlands. In: Menotti, F. and O'Sullivan (Eds.): The Oxford Handbook of Wetland Archaeology, Oxford University Press 2013.

Christensen, K., Eckstein, D, Schmidt, B., (2007): Bronze age coffins in Denmark and North Germany – dendrochronological dating and archaeological implications. Germania 85 (1), 35-46.

Coles, B., Coles, J. (1992): Passages of time. Archaeologische Mitteilungen aus Nordwestdeutschland 15, Oldenburg 1992, 29-44.

Collis, J. (2003): The European Iron Age. Taylor & Francis e-Library 2003, first published by B.T. Batsford 1984, 17.

Dauskane, I., Brumelis, G., Elferts, D. (2011): Effect of climate on extreme radial growth of Scots pine growing on bogs in Latvia/Kliima moju hariliku manni ekstreemsele radiaalkasvule Lati rabades. Estonian Journal of Ecology, 60 (3), 236-248.

Delorme, A., Leuschner, H.H., Tüxen, J., Höfle, H.-C. (1983): Der subatlantische Torfeichen-Horizont »Sieden«, erneut belegt im Toten Moor am Steinhuder Meer. Telma 13, 33-51.

Eckstein, J., Leuschner, H.H., Bauerochse, A., Sass-Klaassen U. (2009): Subfossil bog-pine horizons document climate and ecosystem changes during the Mid- Holocene. Dendrochronologia 27, 129-146.

Eckstein, J., Leuschner, H.H., Giesecke, T., Schumilovskikh, L., Bauerochse, A. (2010): Dendroecological investigations at Venner Moor (northwest Germany) document climate-driven woodland dynamics and mire development in the period 2450–2050 BC. The Holocene 20, 2, 231-244.

Eckstein, J., Leuschner, H.H., Bauerochse, A. (2011): Mid-Holocene pine woodland phases and mire development – significance of dendrochronological data from subfossil trees from nortwest Germany. Journal of Vegetation Science 22, 781-794.

Edvardsson, J., Leuschner, H.H., Linderson, H., Linderholm, H.W., Hammarlund, D. (2011): South Swedish bog pines as indicators of Mid-Holocene climate variability. *Dendrochronologia* 30, 93-103.

Fansa, M., Schneider, R. (1996): Die Moorwege im großen Moor und im Aschener-Brägeler Moor. Archäologiosche Mitteilungen aus Nordwestdeutschland 1996, 5-66.

Gronenborn, D. (2006): Climate change and socio-political crises: some cases from Neolithic Central Europe. Journal of Conflict Archaeology, Vol. 2, no. 1, 3-32.

Hughes P.D.M., K.E. Barber (2004): Contrasting pathway to ombrotrophy in three raised bogs in Ireland and Cumbria, England. The Holocene 14 (1), 65-77.

Leuschner, H.H., Delorme, A., Tüxen, J., Höfle, H.-C. (1986): On oak horizons in mires near the coast of Ostfriesland. Telma 16, 61-83.

Leuschner, H.H., Sass-Klaassen U., Jansma, E., Baillie, M.G.L., Spurk, M., (2002): Subfossil

European bog oaks: population dynamics and long-term growth depressions as indicators of changes in the Holocene hydro-regime and climate. The Holocene 12, 695–706.

Leuschner, H.H., Bauerochse, A., Metzler, A., (2007): Environmental change, bog history and human impact around 2900 B.C. in NW Germany – preliminary results from a dendroecological study of a sub-fossil pine woodland at Campemoor, Dümmer Basin. Vegetation History and Archaeobotany 16, 183–195

Leuschner, H. H., Sass-Klaassen U. (2003): Subfossil oaks from bogs in NW Europe as a (dendro)archaeological archive. In: Bauerochse, A., Haßmann, H. (Eds.): Peatlands – archaeological sites, archives of nature, nature conservation, wise use. Rhaden/Westf., 210–216.

Metzler, A. (2003): Early Neolithic peatland sites around lake Duemmer. In: Bauerochse, A., Haßmann, H. (Eds.): Peatlands. Archaeological sites, archives of nature, nature conservation, wise use. Proceedings of the Peatland Conference 2002 in Hannover, Germany, 62-67.

Metzler, A. (2006): Moorarchäologie in Niedersachsen. In: Fansa, M.; Both, F. (Eds.): Archäologie, Land, Niedersachsen: 25 Jahre Denkmalschutzgesetz – 400.000 Jahre Geschichte. Archäologische Mitteilungen aus Nordwestdeutschland, Beiheft 43; Landesmuseum Natur und Mensch Oldenburg, 471-475.

Moir, A.K., Leroy, S.A.G., Brown, D., Collins, P.E.F. (2010): Dendrochronological evidence for a lower water-table on peatland around 3200-3000 BC from subfossil pine in northern Scotland. The Holocene 20 (6), 931-942**.**

Overbeck, F. (1975): Botanisch-geologische Moorkunde - unter besonderer Berücksichtigung der Moore Nordwestdeutschlands als Quellen zur Vegetations-, Klima- und Siedlungsgeschichte. Karl Wachtelholz Verlag Neumünster.

Plunkett, G., Macdermott, C. Swindles, G.T., Brown, D. (2013): Environmental indifference? A critique of environmentally deterministic theories of peatland archaeological site construction in Ireland. Quaternary Science Reviews 61, 17-31.

Raftery, B., (1996): Trackway excavations in the Mountdillon bogs. Irish archaeological wetland unit.

Schmidt, B. (1992): Hölzerne Moorwege als Untersuchungsobjekt der Dendrochronolgie. Archaeologische Mitteilungen aus Nordwestdeutschland 15, 147-159.

Schwartz, W. (1990): Besiedlung Ostfrieslands in ur- und frühgeschichtlicher Zeit : Klassifikation des Feuersteinmaterials von Oberflächenfundplätzen. Abhandlungen und Vorträge zur Geschichte Ostfrieslands; 71. Ostfriesische Landschaft, Aurich, 109-134.

Spurk, M., Leuschner, H.H., Baillie, M.G.L., Briffa, K.R., Friedrich, M. (2002): Depositional frequency of German subfossil oaks: climatically induced fluctuations in the Holocene. The Holocene 12, 6, 707-715.

Tahvanainen, T. (2011): Abrupt ombrotrophication of a boreal aapa mire triggered by hydrological disturbance in the catchment. Journal of Ecology, Vol. 99, 404–415.

Van Breemen, N. (1995): How sphagnum bogs down other plants. Tree 10, 270-275.

Van Geel, B., Buurman, J., Waterbolk, H.T. (1996): Archaelogical and paleoecological indications of an abrupt climate change in The Netherlands, and evidence climatological teleconnections around 2650 BP. Journal of Quaternary Science, Vol. 11, 451-460.

Van Geel, B., Jansma, E., Van der Plicht, H. (2009): Het oerbos van Diemen en de gevolgen van verminderde zonne-activiteit rond 850 voor Chr. In: Blok, H., Krook, W., van reenen, P., Wiggers, R. (Eds.): Diemen in het land van Amstel, 338-350.

Von Bülow (1935): Die Bedeutung der Versumpfung für die Entstehung von Hochmooren in Deutschland. Geologische Rundschau 26 (4), 277-284

Waterbolk, H.T. (1962): Hauptzüge der eisenzeitlichen Besiedlung der nördlichen Niederlande. Offa Vol.19, 9-46.

Wazny, T. (1994): Dendrochronology of Biskupin – Absolute dating of the Early Iron-Age Settlement. Bulletin of the Polish Academy of Sciences Biological Sciences, Vol. 42, No. 3, 1994.

Manuscript 2: ZDGG Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 168 (1), 9-19

The Göttingen tree-ring chronologies of peat-preserved oaks and pines from northwest Germany

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Die Göttinger Jahrring-Chronologien nordwestdeutscher Eichen und Kiefern aus Torferhaltung

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Zusammenfassung

Die nordwestdeutsche Jahrring-Chronologie aus in Torf konservierten Kiefern (Fig. 1) erstreckt sich mittlerweile von 6703 bis1166 v. Chr., wobei sie noch zwei zeitliche Lücken aufweist. Sie wurde mithilfe der bestehenden Eichen-Chronologie datiert. Umgekehrt wurde der ältere Teil der Eichen-Chronologie, die nun 6628 bis 6178 v. Chr. zusätzlich zur bisherigen Spanne von 6069 v. Chr. bis 931 n. Chr. abdeckt, auf Basis der Kiefern-Chronologie datiert (Fig. 2). Im Vergleich zu den Eichen, wurden von den kurzlebigen Kiefern große Mengen von Proben zur Erstellung einer Chronologie benötigt, von denen viele undatiert oder lediglich relativ-datiert blieben. Der dendrochronologische Prozess, der zeitweise zahlreiche relativ-datierte Mittelkurven hervor brachte, wurde durch eine größere Zahl von Radiokarbon-Datierungen ergänzt. Sowohl vor als auch nach der Zeitspanne der Kalenderjahr-datierten Kiefern-Chronologie liegen Radiokarbon-datierte Mittelkurven vor. Dieses Kiefern-Material ist teilweise zurück bis ins beginnende 9. Jahrtausend v. Chr datiert und dokumentiert Umweltbedingungen des frühen Holozäns. Außerdem zeigt es das Potenzial der Kiefern-Chronologie zur zeitlichen Erweiterung. Die nordwestdeutsche Kiefern-Chronologie war bereits die Basis für Datierungen, u.a. archäologischer Funde wie jungsteinzeitlicher Moorwege. Darüber hinaus sind die Kiefern vor allem für die umweltgeschichtliche Forschung von Bedeutung, da sie an Standorten wuchsen, an denen sie auf hydrologische Schwankungen empfindlich reagieren. Insbesondere die klimatisch beeinflussten Phasen verstärkter Hochmoor-Ausbreitung spiegeln sich in dem Material deutlich wider.

Abstract

To date, the tree-ring chronology of peat-preserved pines from northwest Germany (Fig. 1) spans from 6703 BC to 1166 BC, but still contains two gaps. It was dated with the help of the previously constructed bog-oak chronology of northwest Germany, the older part of which in turn has been dated using the pine chronology (Fig. 2), now covering from 6628 to 6178 BC additional to the previous span of 6069 BC to 931 AD. Compared to the oaks, chronology construction required large numbers of samples were needed of the short-lived pine trees, many of which remained undated or dated relatively only. The dendrochronological process, which at times delivered a multitude of floating chronology fragments, was complemented by a number of radiocarbon dates. Preceding and following the calendar-dated pine chronology, there are radiocarbon dated floating chronologies. This pine record partly dates back to the beginning of the 9th millennium BC and documents environmental conditions during the early Holocene. It also shows the potential of the chronology to be extended further into the past.

The northwest German pine chronology has since been the base for dating i.a. archaeological finds, such as Neolithic wooden bog trackways. Moreover, the peat-preserved pines have proved to be valuable in paleoenvironmental research, as they grew at sites where they were sensitive to hydrological changes. Particularly the climate-related advances of raised bog are well reflected in the material.

Keywords

Dendrochronology, Radiocarbon, bog oak, bog pine, Holocene, Germany

Schlüsselwörter

Dendrochronologie, Radiokarbon, Mooreiche, Moorkiefer, Holozän, Deutschland

1. Introduction

Tree-ring chronologies provide a precise dating tool for wooden finds and have also been the base for the radiocarbon calibration curve (Reimer et al. 2009). Moreover, they are precisely dated environmental records with high temporal resolution. Knowledge of past climate changes is valuable in context of the present one.

The German subfossil oaks (*Quercus spec*, probably *Quercus robur*) have been important archives for the establishment of long postglacial tree-ring chronologies in Europe (Leuschner & Delorme 1988, Spurk et al. 1998, Pilcher et al. 1984, Baillie 1995: 27). While the longer oak chronologies have been built from riverine material originating from southern and central Germany investigated at Hohenheim and Göttingen, reaching back as far as 8480 BC and 7197 BC, respectively (Spurk et al. 1998), the peat-preserved trees from northwest Germany (Fed. State of Lower Saxony), as well have proven valuable, in particular for paleoenvironmental research. The Lower Saxonian Bog Oak Chronology (LSBOC) was established largely in the 1980's (Leuschner et al.1986, Leuschner & Delorme 1988, Leuschner et al. 2002) in mutual cross-dating with the Göttingen chronology of riverine oak material from central Germany (7197 BC – 1136 AD). LSBOC is connected to the present by oak chronologies of historical and archaeological material, now covering the period 610 BC – 2013 AD continuously (Fig. 2). Sample collection and chronology construction have been carried out in the dendrochronological laboratory of the University Göttingen and – in case of archaeological samples – by DELAG (DEndrochronologisches LAbor Göttingen), which cooperates with the University.

Since 2005 work at the Göttingen University dendrochronological laboratory focuses on subfossil pines (*Pinus sylvestris*) from peatland sites in Lower Saxony. Eckstein et al. (2009) published first results of the pine chronology construction from northwest Germany, then covering large parts of the period from 5600 BC to 2200 BC.

Even though the largest part of the wooded Postglacial in Germany has already been covered by tree-ring chronologies, dendrochronological work is not finished. The time span of the chronologies is still being extended, and gaps are being filled. The dendrochronological archive is also being extended in other ways: improving the spatial coverage, constructing chronologies from different tree-species and chronologies from different site-types. Spacial coverage accounts for meteorological variations within the area. Different tree species react differently to environmental parameter like temperature or humidity, as do trees from different site-types. This shows in the differences between the chronologies of oak and pine, and in those between the chronologies of riverine oak and peat-preserved oak. Enlarging the dendrochronological archive in this way increases the likelihood of dating success and greatly enhances it's potential for environmental reconstruction.

The oak chronologies are the backbone of dendrochronology in Germany, as ring-porous oaks can be relied on forming a tree-ring each year. They provided the dating base for the presently studied pines and, of course, the dating of a number of wooden objects and constructions. Moreover, they have yielded valuable insights into the past environment. For example, comparison of the temporal distribution and age structure of the northwest German oaks with those of Dutch and Irish oaks revealed periods of good accordance, implying common climate conditions (Leuschner et al. 2002). Despite the abundance of peat-preserved pine remains in northwest German peatlands, dendrochronological research has focussed on them only recently, since 2006 (Leuschner et al. 2007). A previous pilot study had encountered problems with this material, since the sampled pines contained few rings only, mostly less than 70. The tree-ring series of these pines matched poorly, and it had not been possible to cross-date first site chronologies to the LSBOC. Unlike oak, pine can skip ring formation, even for several years in a row (missing rings). Sometimes just a few cells of a ring are formed in small sections of the circumference (wedging rings). While there are normally no rings missing in forests with better growing conditions, missing rings are quite common at the 'fight-for-survival'-stands the bog-pines grew at.

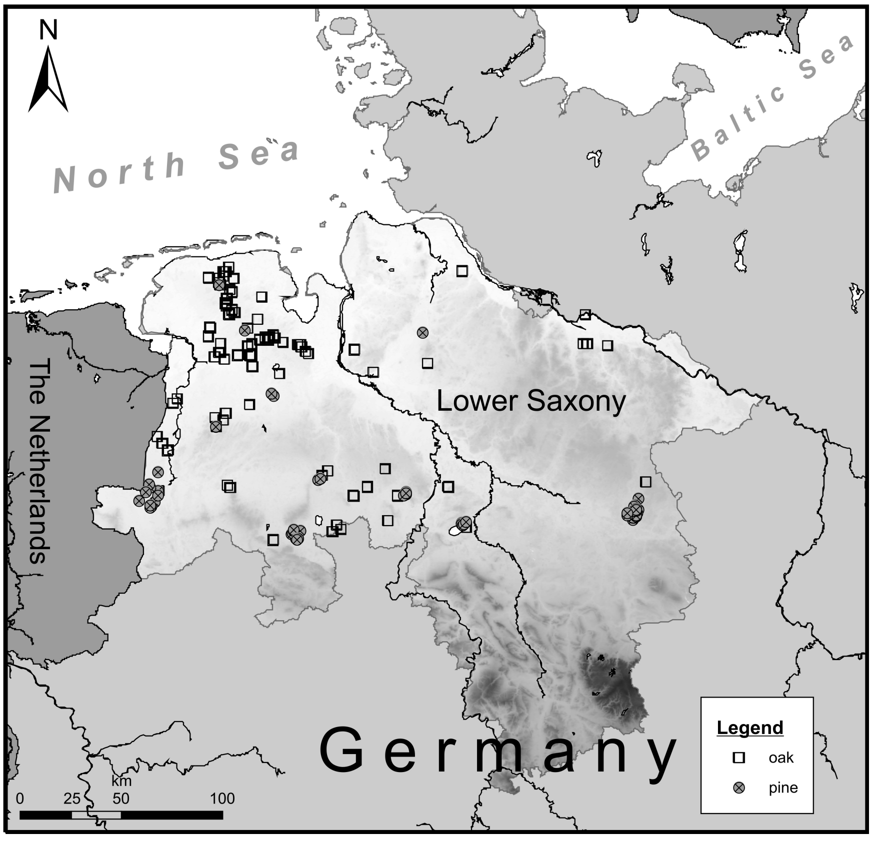

Figure 1: Map of northwest Germany with sample sites of peat-preserved trees. Elevations a.s.l. are shaded for the study area (Fed. State of Lower Saxony).

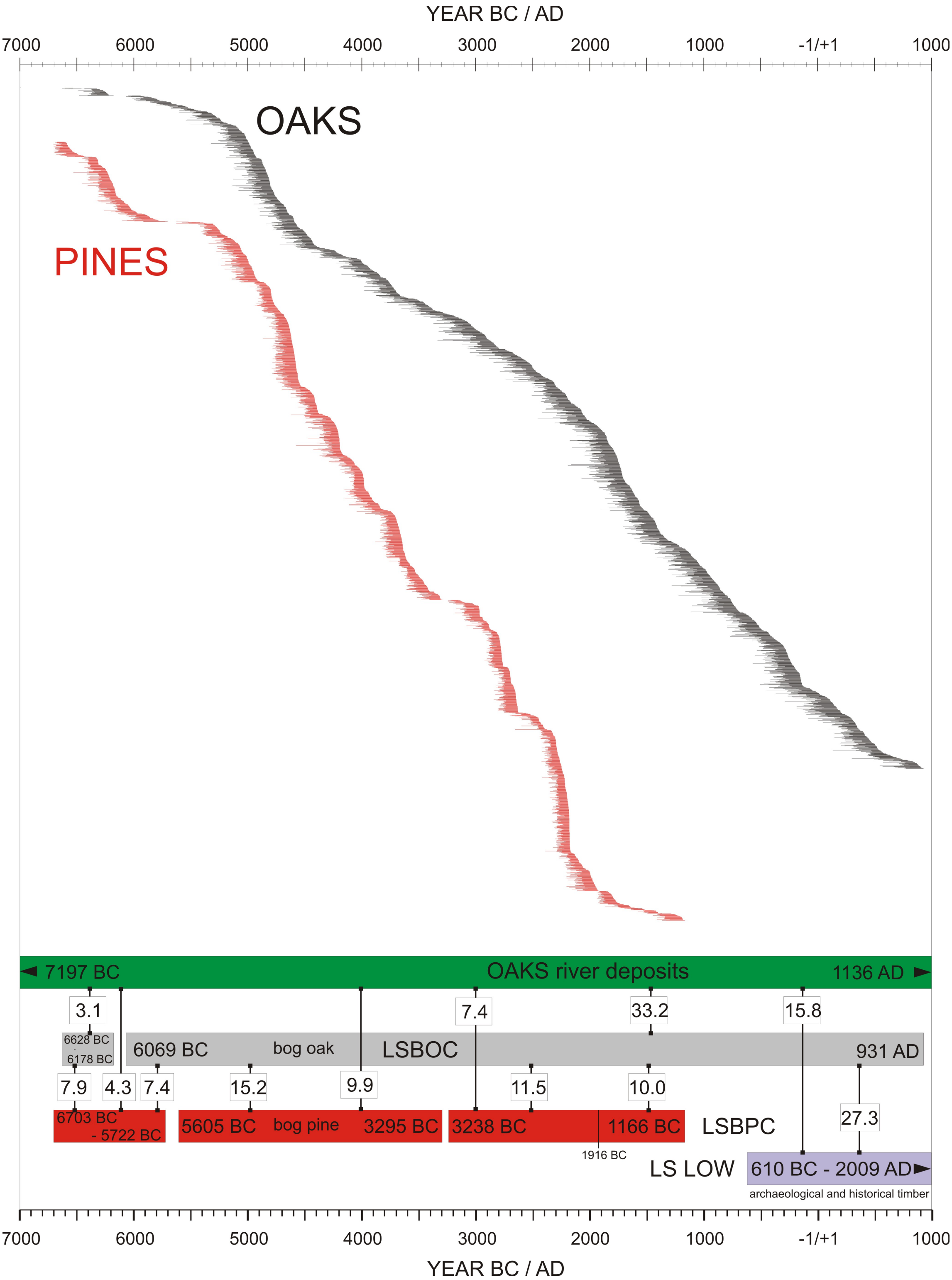

Figure 2: Above: Life-spans of the calendar-dated oaks (black) and pines (red) from northwest German mires, sorted by die-off dates. Notable are the shorter life-spans in comparison to the oaks, and more distinct phases of tree-establishment and high mortality of the pines.
Below: The coverage of the four Göttingen tree-ring chronologies (top to bottom: riverine oaks from northern and central Germany '*OAKS*', oaks from northwest German mires '*LSBOC*', pines from northwest German mires '*LSBPC'*, historical and archaeological oaks dated in Göttingen '*LS LOW*') and the t-values of the cross-dating between them. The third part of the pine chronology (3238-1166 BC) actually consists of two parts, intersected at 1916 BC. There is no gap in between, but they are treated separately due to lack of overlap.

However, this pine material provides a valuable paleoenvironmental record. Dendrochronological studies of the pine material, which is present in abundance at the fen-bog-transition (Overbeck 1975: 52 ff.), allows paleoenvironmental reconstructions of the Holocene bog developement on a high level of temporal and spatial precision. Moreover, the pine chronology provides an appropriate dating tool for other tree-ring chronologies and archaeological finds.

In this paper we present the current state of oak and pine tree-ring chronologies from northwest German mires, which both have substantially been extended since the last published state (Eckstein et al. 2011, Leuschner et al. 2002). We describe the construction of the tree-ring chronology of peat-preserved pines from northwest Germany and the radiocarbon-dated floating chronologies beyond its timespan. Furthermore, we shortly outline the work with this particular paleoenvironmental record.

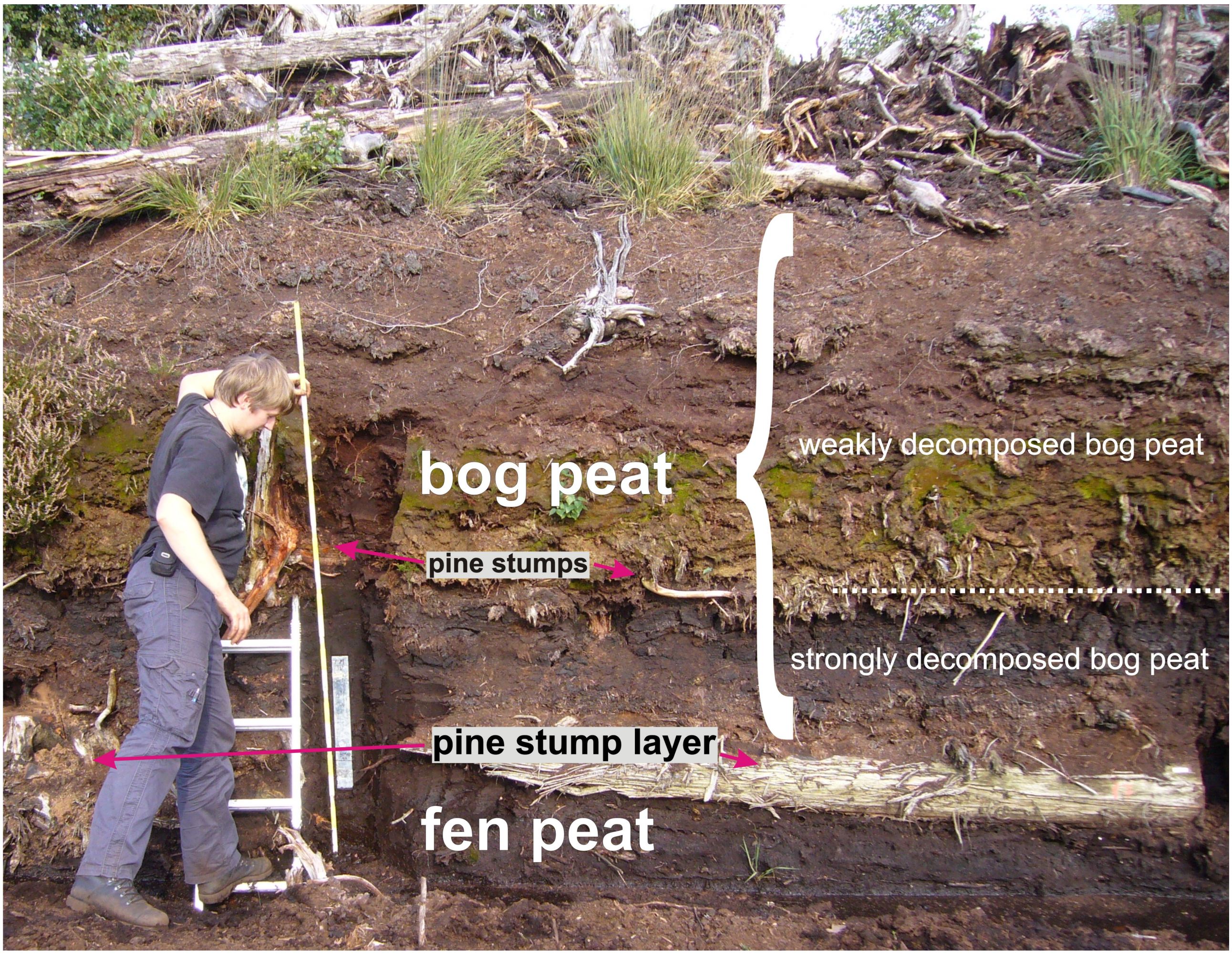

Figure 3: Stratigraphy of the raised bog ‚*Totes Moor*‘ (Hanover District, northwest Germany). Weakly decomposed raised bog peat above strongly decomposed raised bog peat with small pines in the lower part. Below that, fen peat is found, the fen-bog-transition being characterized by a layer of large pine stumps. Photo: Jan Eckstein.

2. Material and Methods

Northwest Germany largely consists of lowlands stretching between North Sea coast and the central hill-lands (Fig.1). This plain had been covered in large parts by peatland (Overbeck 1975: 210), before the mires were drained and largely put into agricultural use. There were numerous ground-water influenced fens along rivers and huge raised bogs up to 10 m high, supplied exclusively by rainwater. The expansion of the latter had started around 7000 BC (Behre 2008: 46) and would even continue today, had the area not been drained.

The reconstruction of raised bog expansion through space and time is possible on the base of numerous peat preserved tree remains from peatland all over northwest Germany (Fig. 1). They are exposed in the course of industrial peat extraction, mostly originate from the fen-bog-transition (Fig. 3), and testify shifts in Holocene climate conditions.

The dendrochronological cross-dating was performed following traditional techniques (Schweingruber 1988), the inter-series accordance was quantified using Baillie-Pilcher t-values (Baillie & Pilcher 1973) and an adjusted version thereof with a triangular influence weighting of the rings, developed by T. Riemer. Specifics of the cross-dating of the peat-preserved pines are described in Leuschner et al. (2007). Dating software used included the *V-program*-set by Thomas Riemer (Riemer 1994) and *TSAPWin professional* version 4.69d by Rinntech (Rinn 2003).

Some specifics of the northwest German peat-preserved pine material, which affect the dendrochronological practice are: 1) missing rings, sometimes several in succession, and wedging rings, at times with only a hand full of cells to be found around the circumference; 2) large variability in climate-growth relationships, depending on site conditions (Fig. 4); 3) short life-spans (Fig. 2); and 4) occurrence in phases, with little overlap of life spans (Fig. 2). The initial difficulties

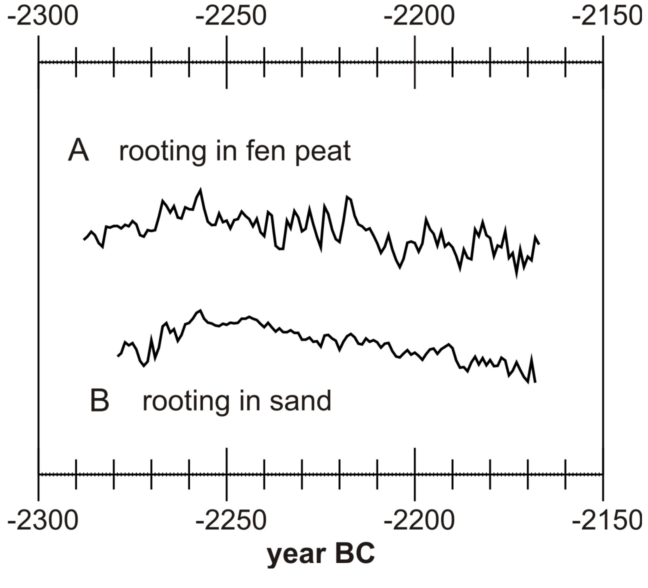

Figure 4: On different substrates, the growth-reactions of the trees to the varying climatic influences differ greatly. Two contemporary tree-ring-width mean curves (of ten pines each) from one plot are shown: The pines in the upper plot (A) rooted in fen peat, while the others (B) rooted into the sand below. The pines in A and B grew less than 200 m apart, and therefore the climatic influences can be assumed to have been identical.

in cross-dating the pines were met by i) taking at least 50 samples from each site; ii) then generating relative dated site-chronologies; iii) then dating site-chronologies from different sites relative to each other. The longer chronology-fragments obtained were then dated on the northwest German Oak Chronology (LSBOC). While temporal expansion (Fig. 2), replication (Fig. 5), and spatial coverage (Fig. 1) of the pine chronology increased, individual pine samples became increasingly better datable on the pine chronology directly.

The dendrochronological construction of the northwest German pine chronology was supported by 105 radiocarbon dates from the radiocarbon laboratory at the Leibniz Institute for Applied Geophysics (LIAG) in Hannover (Table 2) and by 25 radiocarbon dates from the Curt-Engelhorn-Center for Archaeometry gGmbH in Mannheim (not listed). Wiggle matching was carried out, most of all for samples relatively dated within floating chronologies, using the *OxCal* online program (Bronk Ramsey et al. 2001, Bronk Ramsey 2009, Reimer et al. 2009).

In addition to the samples dated within the framework of the pine chronology construction, 26 measurements were carried out by the LIAG laboratory to radiocarbon-date all stockworks of *in situ* pine layers which were found within a peat profile at a location within site '*Totes Moor*' ('*TORG')*. This stratigraphic and ecological study (Bauerochse et al. 2009) included pines with diameters below 10 cm and few tree-rings only, which were not suitable for dendrochronology.

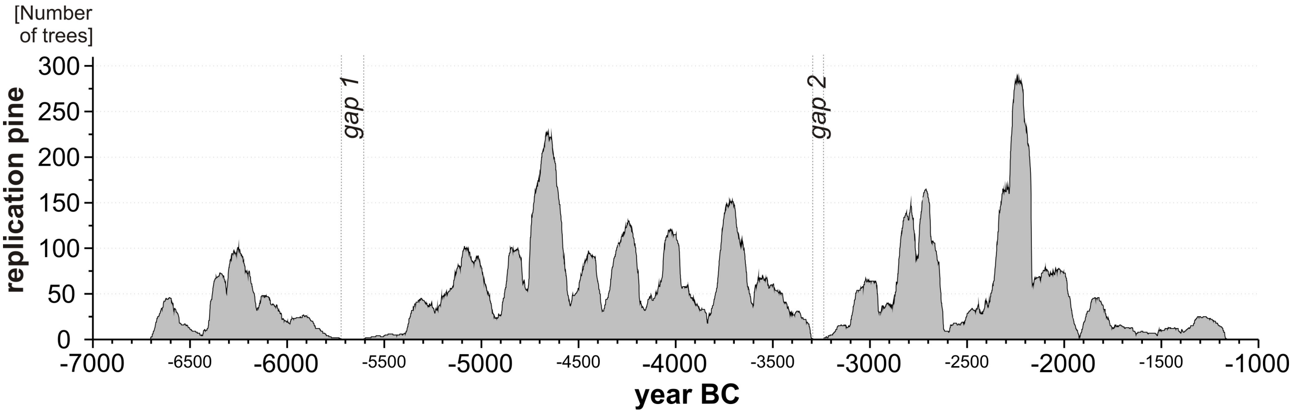

Figure 5: Replication of the northwest German pine chronology.

3. Results

Figure 2 shows the present state of the bog oak and bog pine chronologies and the distribution of single tree-ring series therein. It also shows the inter-chronology *t*-values. The dates of the oak chronologies are confirmed by cross-dating with other German and European oak chronologies (Spurk et al. 1998, Baillie 1995). The number of samples per calendar-year (replication) of the pine chronology is shown in Fig. 5, further illustrating the phases of establishment and die-off of the subfossil pine woodland.

3.1. Oak chronology

The last published state of the northwest German chronology of peat-preserved oaks contained 1561 trees and covered the time span from 6069 BC to 931 AD (Leuschner et al. 2002). Since then, additional 529 subfossil bog oaks have been investigated, dendrochronologically dated and added to the chronology. Today, the LSBOC contains tree ring widths of 2090 oaks, covering the periods 6628 to 6178 BC and 6069 BC to 931 AD. The older part of the chronology has been dated on the base of the northwest German pine chronology. The two parts of the chronology cover 451 and 7000 years respectively. The gap at the time of the 8.2k-Event is 108 years long. The average length of the oak tree-ring-series is 162 years.

3.2. Pine chronology

Until now around 5300 peat-preserved pine trees have been sampled, 2884 of which are dendrochronologically dated. Compared to the last published state (Eckstein et al. 2011), this is an increase by 1641 dated trees. The temporal coverage of the northwest German chronology of peat-preserved pines has also been significantly extended, and now covers the time spans 6703 - 5722 BC, 5605 – 3295 BC and 3238 – 1166 BC (Fig. 2). The chronology segments cover 982, 2311 and 2073 years respectively, the gaps being 116 and 56 years long. The calendar-dated pine samples count 107 rings on average, while 99% of the pines have less than 222 rings and only one tree featured over 300 tree-rings, counting 385 rings. Thereby the pines show much shorter life-spans in comparison to the oaks. Also, the phases of regeneration and common die-off phases of the pines are documented throughout the region (Fig. 2).

The northwest German chronologies of peat-preserved pine and oak cross-date well with each other, and also with the chronology of north and central German riverine oaks (t-values given in Fig. 2). The younger parts also cross-date well with the Göttingen chronology of historic oak timbers (Fig. 2).

3.3. Radiocarbon dates

Although the pine chronology was built entirely based on dendrochronological cross-dating, the process of chronology construction, which at times involved numerous floating chronologies, was significantly sped up and re-confirmed by the radiocarbon age determinations. Table 2 displays the results of the radiocarbon analyses carried out at LIAG. Many dates belong to floating chronologies, some of which are outside the range of the calendar-dated tree- ring chronologies. The radiocarbon dates of samples, which (meanwhile) have dendrochronological calendar-dates, are in agreement with those dates.

One radiocarbon-dated floating chronology covers the second of the remaining gaps in the pine chronology. Four floating chronologies were radiocarbon-dated to times before and after the span of the calendar-dated chronology. These radiocarbon dated floating chronologies imply the potential for further extension of the pine chronology. They document the presence of pine material both younger and older than the reach of the calendar-dated chronology (Table 1). The ^{14}C-dated pines of these four floating chronologies show 129 rings on average.

The floating chronology *M72N_RD1* begins, according to ^{14}C dates, very close to the end of the calendar-dated chronology. The floating chronologies *M914_RD1*, *M914_RD2* and *M72S_RD1* date before the beginning of the northwest German calendar-dated tree ring chronologies. They extend between 300 and 500 years. Radiocarbon age determination date them to the early 9th, late 9th and early 7th millennia BC (Table 1). The gap between the latter and the calendar-dated chronology is about one hundred years. The lengths of the other two gaps are about 850 years and 300 years, respectively.

Table 1: Floating pine chronologies outside the present range of the calendar-dated chronology.
^{1}: dated by M. Frechen, LIAG, Hannover, ^{2}: dated by B. Kromer, Heidelberg.

Name	**Length [years]**	**Number of samples**	**Approx. timespan [cal. ^{14}C]**	**Gap to next chronology [years]**
M914_RD1	373	58	c. 9100 – 8750 BC^{2}	c. 300
M914_RD2	503	57	c. 8450 - 7950 BC^{2}	c. 850
M72S_RD1	309	34	c. 7100 - 6800 BC^{1}	c. 100
M72N_RD1	246	56	c. 1150 - 900 BC^{1}	c. 15

Table 2: List of ^{14}C dates. The sample IDs of the ^{14}C laboratory (HV) and the dendrochronological laboratory (LABEL) are given, the ^{14}C age (^{14}C Dat) with its range (VAR) and calibrated ^{14}C date (cal.^{14}C). Cal. ^{14}C was obtained on base of *IntCal13* (Reimer et al. 2013), using *Oxcal online* Program (Bronk Ramsey et al. 2001, Bronk Ramsey 2009), giving the 95.4 probability range in years BC. The dendrochronological calendar-date (Dendro-Date) is given for the middle of the ^{14}C-dated sample in years BC. The present status of a given sample in dendrochronological dating, or the context of samples not suitable for dendrochronological dating respectively, is listed (Sample status), with "relatively dated" meaning dated within a floating tree ring chronology, and "ecological study" referring to investigated tree layers not suitable for dendrochronological dating.

HV	LABEL	$_{14}$C Dat	VAR	cal. $_{14}$C	Dendro-date	Sample status (dendrochronological)
26088	M729A9FA	7680	50	BC 6612 - 6441	BC 6617	calendar-dated
25476	M7230910	7705	50	BC 6636 - 6462	BC 6609	calendar-dated
25490	M7232410	7675	45	BC 6600 - 6443	BC 6593	calendar-dated
26089	M729A9FB	7710	60	BC 6646 - 6453	BC 6587	calendar-dated
26080	M723M3BA	7725	45	BC 6640 - 6473	BC 6580,5	calendar-dated
26081	M723M3BB	7710	45	BC 6633 - 6466	BC 6497,5	calendar-dated
26082	M723P4_0	7725	50	BC 6642 - 6470	BC 6493	calendar-dated
25478	M72357_0	7360	55	BC 6372 - 6085	BC 6355	calendar-dated
25494	M31712_A	7330	50	BC 6354 - 6065	BC 6292,5	calendar-dated
25474	M7232210	7420	60	BC 6430 - 6106	BC 6271,5	calendar-dated
25483	M72302B0	6250	60	BC 5352 - 5046	BC 5298,5	calendar-dated
25493	M90712_A	6120	45	BC 5211 - 4944	BC 5120	calendar-dated
25492	M1441320	6155	45	BC 5221 - 4981	BC 5041,5	calendar-dated
25482	M350521A	5855	60	BC 4848 - 4547	BC 4810	calendar-dated
25475	M350151A	5790	55	BC 4780 - 4517	BC 4668,5	calendar-dated
25650	M91202FB	5735	50	BC 4701 - 4465	BC 4556,5	calendar-dated
25489	M72431_0	5540	45	BC 4464 - 4327	BC 4420	calendar-dated
25473	M140371A	5570	45	BC 4488 - 4341	BC 4385	calendar-dated
25651	M9123210	5500	45	BC 4452 - 4261	BC 4337,5	calendar-dated
25658	M724G8F0	5415	45	BC 4354 - 4072	BC 4257,5	calendar-dated
25653	M726661A	5260	45	BC 4232 - 3977	BC 4130,5	calendar-dated
25477	M14213F0	5280	45	BC 4236 - 3988	BC 4093,5	calendar-dated
25654	M7266310	5055	45	BC 3962 - 3715	BC 3853,5	calendar-dated
25655	M72682FB	4845	45	BC 3710 - 3522	BC 3691,5	calendar-dated
25484	M113B6_B	4730	45	BC 3636 - 3376	BC 3616	calendar-dated
25486	M11368_A	4760	45	BC 3644 - 3377	BC 3582,5	calendar-dated
25656	M724J3F0	4685	45	BC 3631 - 3365	BC 3506,5	calendar-dated
26085	M724R9_0	4665	45	BC 3628 - 3360	BC 3462	calendar-dated
26086	M724S3FB	4425	50	BC 3335 - 2917	BC 3341	calendar-dated
25645	M73406_0	4500	55	BC 3365 - 3022	BC 2967,5	calendar-dated
26095	MD01J1FA	4120	50	BC 2876 - 2506	BC 2815	calendar-dated
25829	MD0134_1	4025	45	BC 2848 - 2462	BC 2789	calendar-dated
26105	MD0682FA	4065	50	BC 2862 - 2473	BC 2731	calendar-dated
26106	MD0682FB	4090	45	BC 2870 - 2491	BC 2697	calendar-dated
26107	MD06A1F0	4065	45	BC 2859 - 2475	BC 2675	calendar-dated
26103	MD048710	3945	50	BC 2574 - 2294	BC 2569	calendar-dated
26104	MD04B8_0	3910	50	BC 2565 - 2209	BC 2476,5	calendar-dated
25827	MD01B8F0	4170	70	BC 2904 - 2573	BC 2475	calendar-dated

25479	M90404_0	3910	55	BC 2566 - 2208	BC 2367	calendar-dated
25642	MD0244F0	3810	45	BC 2458 - 2136	BC 2244,5	calendar-dated
25643	MD0293F0	3870	60	BC 2487 - 2145	BC 2168,5	calendar-dated
25647	M91071F0	3610	45	BC 2135 - 1786	BC 2124,5	calendar-dated
25652	M91223F0	3700	45	BC 2266 - 1951	BC 2082,5	calendar-dated
25491	MD04A2_B	3535	45	BC 2012 - 1746	BC 1879	calendar-dated
26100	MD0475F0	3500	45	BC 1940 - 1694	BC 1866	calendar-dated
26096	MD0303_A	3225	45	BC 1612 - 1423	BC 1611	calendar-dated
25481	MD0320_A	3260	45	BC 1631 - 1436	BC 1590	calendar-dated
26097	MD0303_A	3280	50	BC 1681 - 1445	BC 1527	calendar-dated
26094	M73566F0	3100	50	BC 1494 - 1227	BC 1404	calendar-dated
25657	M724F2F0	3135	45	BC 1500 - 1286	BC 1306,5	calendar-dated
26091	M73519F0	3140	45	BC 1501 - 1292	BC 1426	calendar-dated
25480	M139401A	4070	45	BC 2861 - 2477		relatively dated
26134	M1394410	3700	50	BC 2275 - 1945		relatively dated
26135	M13963_0	4710	50	BC 3635 - 3371		relatively dated
26077	M723061A	7975	45	BC 7049 - 6701		relatively dated, outside of chronology-span
26078	M723061B	7935	45	BC 7034 - 6685		relatively dated, outside of chronology-span
26079	M723061C	7910	50	BC 7029 - 6649		relatively dated, outside of chronology-span
25487	M7230710	7950	50	BC 7041 - 6691		relatively dated, outside of chronology-span
26083	M724J9F0	4495	45	BC 3356 - 3029		relatively dated, chronology-gap
26084	M724L9F0	4540	45	BC 3482 - 3095		relatively dated, chronology-gap
26087	M7291610	3130	45	BC 1499 - 1285		relatively dated
26090	M729F2_A	7900	60	BC 7032 - 6642		relatively dated, outside of chronology-span
25644	M73402_0	4530	45	BC 3370 - 3091		relatively dated
25646	M73421_A	4895	60	BC 3906 - 3527		relatively dated
26092	M73529F0	3610	45	BC 2135 - 1786		relatively dated
26093	M73540F0	3220	50	BC 1616 - 1411		relatively dated
25648	M91077F0	4425	55	BC 3335 - 2916		relatively dated, chronology-gap
25649	M91130F0	3280	45	BC 1662 - 1450		relatively dated
25830	M91138F0	3240	45	BC 1617 - 1430		relatively dated
25828	MD01H6F0	4200	45	BC 2902 - 2635		relatively dated
26098	MD0318_0	3355	50	BC 1754 - 1508		relatively dated
26099	MD0458F0	4460	50	BC 3348 - 2938		relatively dated, chronology-gap
26101	MD0479F0	4325	50	BC 3090 - 2879		relatively dated
26102	MD0486F0	4400	50	BC 3327 - 2906		relatively dated, chronology-gap
25485	M14207F1	5320	45	BC 4318 - 4004		not dated
25472	M14040_0	5790	55	BC 4780 - 4517		not dated
25488	M14023F0	6070	70	BC 5211 - 4803		not dated
26108	M13203_W	8670	50	BC 7822 - 7585		not dated, outside of chronology-span
25832	TORG 13	4445	45	BC 3337 - 2929		ecological study, small pines layer 1
25835	TORG 16	4580	45	BC 3501 - 3102		ecological study, small pines layer 1
25836	TORG 1 B	4610	70	BC 3629 - 3099		ecological study, small pines layer 1
25833	TORG 14	4630	79	BC 3633 - 3104		ecological study, small pines layer 1
25831	TORG 11 FA	4710	45	BC 3534 - 3371		ecological study, small pines layer 1
25837	TORG 21	4455	45	BC 3341 - 2938		ecological study, small pines layer 2
25838	TORG 22	4585	45	BC 3509 - 3103		ecological study, small pines layer 2

25840	TORG 29 F	4695	45	BC 3631 - 1168		ecological study, small pines layer 2
25839	TORG 23	4800	45	BC 3661 - 3382		ecological study, small pines layer 2
25844	TORG 35	2910	45	BC 1231 - 945		ecological study, small pines layer 3
25845	TORG 36	2920	45	BC 1261 - 996		ecological study, small pines layer 3
25859	TORG 3 N	3010	45	BC 1397 - 1118		ecological study, small pines layer 3
25841	TORG 31	3015	45	BC 1398 - 1123	BC 1239	ecological study, small pines layer 3
25843	TORG 34	3015	45	BC 1398 - 1123		ecological study, small pines layer 3
25842	TORG 32	3040	45	BC 1415 - 1131	BC 1259	ecological study, small pines layer 3
25850	TORG 3 D	3040	50	BC 1419 - 1128		ecological study, small pines layer 3
25856	TORG 3 K	3070	45	BC 1431 - 1216		ecological study, small pines layer 3
25849	TORG 3 C	3075	45	BC 1432 - 1221		ecological study, small pines layer 3
25851	TORG 3 E	3115	45	BC 1496 - 1264		ecological study, small pines layer 3
25858	TORG 3 M	3120	45	BC 1497 - 1271		ecological study, small pines layer 3
25853	TORG 3 H	3120	50	BC 1498 - 1265		ecological study, small pines layer 3
25847	TORG 3 AW	3130	45	BC 1499 - 1285		ecological study, small pines layer 3
25854	TORG 3 I	3140	45	BC 1501 - 1292		ecological study, small pines layer 3
25857	TORG 3 L	3175	45	BC 1599 - 1304		ecological study, small pines layer 3
25855	TORG 3 J	3190	45	BC 1608 - 1321		ecological study, small pines layer 3
25848	TORG 3 B	3225	45	BC 1612 - 1423		ecological study, small pines layer 3
26112	TOGR 3X	4675	45	BC 3629 - 3362	BC 3448	ecological study, small pines layer 3

4. Discussion

The northwest German pine chronology has a wide spatial coverage (Fig. 1) and high replication (Fig. 5), making it a valuable master chronology. In particular, the coverage of the east-west transect (Fig. 1) containing a gradient of continentality, results in the robustness of the chronology. By now, individual pine samples can mostly be dated directly using this master chronology. Other dated objects include the excavated Neolithic wooden trackway at Campemoor (Duemmer area), which initiated the work on the northwest German peat-preserved pines back in 2006 AD, that has been dated to 2883 BC (Leuschner et al. 2007), and the oldest known trackway, dated to 4629 BC and following years (Achterberg et al. 2015, Bauerochse et al. 2012). While the construction of the calendar-dated pine chronology was based on the northwest German tree ring chronology of peat-preserved oaks, the oldest part of the northwest German oak chronology (6628 - 6178 BC) was dated on base of the pines. The northwest German pine chronology was also the base for dating south Swedish bog-pine records (Edvardsson 2012). Similarly, the northwest German oaks cross-date well with the Irish bog-oaks (Baillie 1995: 27). These international comparisons verify the correctness of the chronologies, and moreover yield palaeoenvironmental implications (Leuschner et al. 2002, Edvardsson 2012).

However, chronology-construction is not entirely completed. Of the two gaps in the pine chronology, the gap spanning 3294 to 3239 BC is covered by a radiocarbon dated floating chronology, which does not have a secure calendar-date yet. This implies that this gap does not represent a period of tree-less mires, and therefore can be closed by future work. At present, we lack pine material known to cover the gap 5721-5606 BC. This might be indicative for a period with only scattered trees growing on peatlands.

Radiocarbon age determinations are vital, particularly for those floating chronologies, which date outside the range of the calendar-dated tree ring chronologies. Therefore, these floating chronologies can already be used for paleoenvironmental studies. The peat-preserved pine stands in the area were shown to date back as far as the onset of the 9th millennium BC (Table 1), showing the potential for extension of the northwest German chronology. However, to adjoin the floating chronologies to one continuous chronology, an additional vast amount of samples would be required.

The meanwhile well-replicated and largely continuous archive of peat-preserved trees has reached a representative proportion for the studied region. This results from the large number of sites and trees investigated. Together with the extensive documentation of the find-context, particularly by palynological and extensive peat-stratigraphical investigations, this allows for more general evaluations.

The pines have provided insights into past climate dynamics, as recent studies on the peat-preserved pines showed the fluctuating conditions in the raised bog systems of the northwest German lowland (Eckstein et al. 2011, Bauerochse et al. 2012). The northwest German peat-preserved pines depict woodland phases with distinct phases of tree establishment (germination) and tree die-off (Fig. 2). This causes difficulties for chronology construction, because it leads to short and low-replicated overlaps between the woodland phases on the one hand, but on the other hand greatly adds to their specific value in paleoenvironmental research, as these phases are highly indicative of past changes in humidity (Eckstein et al. 2011). The effects of hydrological changes on the bog pines have been examined in a case study at *Venner Moor* (Eckstein et al. 2010). In this study, tree-ring and tree-morphological finds have been combined with peat-stratigraphical and palynological results, depicting the mire development through more than 243 years. A striking synchronicity of wooded phases and common die-off phases was observed in different mires. This concurrent occurrence of die-off and germination events implies a climatic trigger (Eckstein et al. 2009, 2011).

Pine stump layers were typically preserved during the development or expansion of raised bogs over fen peat. As raised bogs are closely dependant on precipitations, their advances imply timing and scale of past hydrological changes. The reconstruction of Holocene raised-bog expansions results from numerous pine remains from all over northwest Germany. According to these results, the raised-bog development initiated in the 7th millennium BC, with a strong increase between 5100 and 3600 BC (Eckstein et al. 2011). This is in accordance with peat-based investigations by Petzelberger et al. (1999).

Ongoing work focusses on the spatio-temporal reconstruction of the development of raised bogs and their expansion during the Holocene. The existing dendrochronological results document phases of rapid advance of rain-fed bogs. They also form the basis for detailed analysis of past climate and environmental change. These large scale investigations of subfossil pine layers in bogs of northwest Germany are unique in their temporal and regional extent and benefited greatly from the availability of material from industrial peat logging, which is due to end soon.

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6. References

Achterberg, I., Bauerochse, A., Giesecke, T., Metzler, A., Leuschner, H. (2015): Contemporaneousness of Trackway construction and environmental change: a dendrochronological study in Northwest-German mires. Interdisciplinaria Archaeologica 6 (1), 19-29.

Baillie, M.G.L., Pilcher, J. (1973): A simple cross-dating program for tree-ring research. Tree Ring Bulletin 33: 7-14.

Baillie, M.G.L. (1995): A Slice Through Time: Dendrochronology and Precision Dating. 176 S. B.T. Batsford, London.

Bauerochse, A., Held, S., Eckstein, J., Leuschner, HH. (2009): Jahr- und millimetergenau: Moorentwicklung und Umweltgeschichte im dendroökologischen Spiegel subfossiler Moorkiefern. Berichte zur Denkmalpflege in Niedersachsen 29: 71-76

Bauerochse, A., Leuschner.H., Metzler, A. (2012): Das Campemoor im Neolithikum. Jahrbuch für das Oldenburger Münsterland 2012, 61. Jahrgang, Heimatbund für das Oldenburger Münsterland.

Behre, K.-E. (2008): Landschaftsgeschichte Norddeutschlands- Umwelt und Siedlung von der Steinzeit bis zur Gegenwart. 308 S., Wachholtz Verlag Neumünster 2008.

Bronk Ramsey, C. (2009): Bayesian analysis of radiocarbon dates. Radiocarbon, 51 (1), pp. 337-360.

Bronk Ramsey, C., van der Plicht, J., Weninger, B.(2001): 'Wiggle matching' radiocarbon dates. Radiocarbon, 43 (2A): 381-389.

Eckstein, J., Leuschner, H.H., Bauerochse, A., Sass-Klaassen, U. (2009): Subfossil bog-pine horizons document climate and ecosystem changes during the Mid- Holocene. Dendrochronologia 27: 129-146.

Eckstein, J., Leuschner, H.H., Giesecke, T., Schumilovskikh, L., Bauerochse, A. (2010): Dendroecological investigations at Venner Moor (northwest Germany) document climate-driven woodland dynamics and mire development in the period 2450–2050 BC. The Holocene 20 (2): 231-244.

Eckstein, J., Leuschner, H.H., Bauerochse, A. (2011): Mid-Holocene pine woodland phases and mire development – significance of dendrochronological data from subfossil trees from northwest Germany. Journal of Vegetation Science 22: 781-794.

Edvardsson, J., Leuschner, H.H., Linderson, H., Linderholm, H.W., Hammarlund, D. (2012): South Swedish bog pines as indicator of Mid-Holocene climate variability. Dendrochronologia 30: 93-103.

Leuschner, H.H., Delorme, A., Tüxen, J., Höfle H.-C. (1986): Über Eichenwaldhorizonte in küstennahen Mooren Ostfrieslands - On Oak Horizons in Mires Near the Coast of Ostfriesland. Telma 16: 61-82.

Leuschner, H.H. & Delorme, A. (1988): Tree ring Work in Goettingen - Absolute Oak Chronologies back to 6255 BC. PACT 22 – II.5: 123-131.

Leuschner, H.H., Sass-Klaassen, U., Jansma, E., Baillie, M.G.L., Spurk, M. (2002): Subfossil European bog oaks: population dynamics and long-term growth depressions as indicators of changes in the Holocene hydro-regime and climate. The Holocene 12: 695–706.

Leuschner, H.H., Bauerochse, A., Metzler, A. (2007): Environmental change, bog history and human impact around 2900 B.C. in NW Germany – preliminary results from a dendroecological study of a sub-fossil pine woodland at Campemoor, Dümmer Basin. Vegetation History and Archaeobotany 16: 183-195.

Moir, A.K., Leroy, S.A.G., Brown, D., Collins, P.E.F. (2010): Dendrochronological evidence for a lower water-table on peatland around 3200-3000 BC from subfossil pine in northern Scotland. The Holocene 20 (6): 931-942**.**

Overbeck, F. (1975): Botanisch-geologische Moorkunde. 719 S., Karl Wachholz Verlag Neumünster.

Petzelberger, B.E.M., Behre, K. & Geyh, M.A. (1999): Beginn der Hochmoorentwicklung und Ausbreitung der Hochmoore in Nordwestdeutschland – erste Ergebnisse eines neuen Projektes. Telma 29: 21–38.

Pilcher, J.R. (1973): Tree-ring research in Ireland. Tree-Ring Bulletin, 33: 1-14.

Pilcher, J., Baillie, M., Schmidt, B., Becker, B. (1984): A 7,272-year tree-ring chronology for western Europe. Nature 312: 150-152.

Reimer, P., Baillie, M., Bard, E., Bayliss, A., Beck, J., Blackwell, P., Bronk Ramsey, C. , Buck, C., Burr, G., Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Hajdas, I., Heaton, T., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., McCormac, F., Manning, S., Reimer, R., Richards, D., Southon, J., Talamo, S., Turney, C., van der Plicht, J., Weyhenmeyer, C. (2009): INTCAL09 and MARINE09 radiocarbon age calibration curves, 0–50,000 Years cal BP. Radiocarbon, 51 (4): 1111–1150.

Reimer, P.,Bard, E., Bayliss, A., Beck, J., Blackwell, P., Bronk Ramsey, C. , Buck, C., Cheng, H., Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T., Hoffmann, D., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., Manning, S., Niu, M., Reimer, R., Richards, D., Scott, M., Southon, J., Staff, R., Turney, C., van der Plicht, J. (2013): IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years cal BP. Radiocarbon, 55 (4) : 1869-1887.

Riemer T. (1994): Über die Varianz von Jahrringbreiten – Statistische Methoden für die Auswertung der jährlichen Dickenzuwächse von Bäumen unter sich ändernden Lebensbedingungen. Berichte des Forschungszentrums Waldökosysteme, Reihe A 121:1–375.

Rinn, F. (2003): TSAP-Win: Time Series Analysis and Presentation for Dendrochronology and related Applications. Version 0.55 User reference. Heidelberg, Germany, www.rinntech.com.

Schweingruber, F. (1988): Tree Rings – Basics and Application of Dendrochronology. 276 S. D. Reidel Publishing Company, Dordrecht, Holland.

Spurk, M., Friedrich, M., Hofmann, J., Remmele, S., Frenel, B., Leuschner, H.H., Kromer, B. (1998): Revisions and extensions of the Hohenheim oak and pine chronologies: new evidence about the timing of the Younger Dryas/Preboreal transition. Radiocarbon, 40 (3): 1107-1116.

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Dendrochronologically dated pine stumps document phase-wise bog expansion at a northwest German site between ca. 6700 and ca. 3400 BC

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Abstract

The investigated northwest German mire site at “Totes Moor” is densely covered with subfossil pine stumps (Pinus sylvestris L.) from the fen–bog transition. This facilitates the spatio-temporal reconstruction of mire development, which is based on 212 in situ tree stumps in the case study presented here. Six dendrochronologically dated site chronologies together cover 2345 years between 6703 and 3403 BC. The gaps in between are 6 to 550 years long. Additionally, a floating chronology of 309 years, containing 30 trees, was radiocarbon-dated to the beginning of the 7th millennium cal BC. Peat-stratigraphical survey was carried out additionally, and elevations a.s.l. were determined at several locations.

Tree dying-off phases, which indicate water level rise at the site, mostly in context of the local fen–bog transition, are evident for ca. 6600–6450, ca. 6350–5750, ca. 5300–4900, ca. 4700–4550, ca. 3900–3850, ca. 3700–3600, ca. 3500–3450 and ca. 3400 BC. The spatial distribution of the dated in situ trees illustrates the phase-wise expansion of raised bog over fen peat at the site. The documented bog expansion pulses likely correspond to climatic wet sifts.

1. Introduction

Raised bog development shaped the northwest German lowland during the Holocene, as eventually about a third of the area had been covered by mires (fens and bogs) (Metzler, 2004). The development of these mires on the underlying nutrient-poor glacial deposits was largely determined by climatic variations (Ellenberg, 1996). The area was particularly characterized by large lowland raised bogs, which grow better under humid and cool conditions (Behre, 2008). The expansion of these raised bogs is evident since the 7th millennium BC, with a strong increase between 5100 and 3600 BC (Eckstein et al., 2011; Petzelberger et al., 1999). The peat in the area contains a valuable environmental record of the past millennia.

The raised bogs were treeless in their central parts, while most of the surrounding region was wooded. Even the fens were wooded in large parts, often forming alder (Alnus) swamp forests or carrying other tree species. Often at the margins of a raised bog a swamp (lagg) develops, fed by runoff water from the bog mixing with ground water. In contrast to the otherwise generally treeless raised bog (Ellenberg, 1996), the more drained margin of the raised bog towards the lagg, is commonly wooded by pine (Pinus sylvestris L.). The expansion of the raised bogs (which can be expected to occur during moist periods) often causes severe growth conditions for bog trees and consequently widespread dying-off phases. The remains of the affected trees are preserved under Sphagnum peat in the process. Stratigraphically the pine stumps mostly mark the local fen–bog transition. When in situ stumps are dated, they document the raised bog expansion.

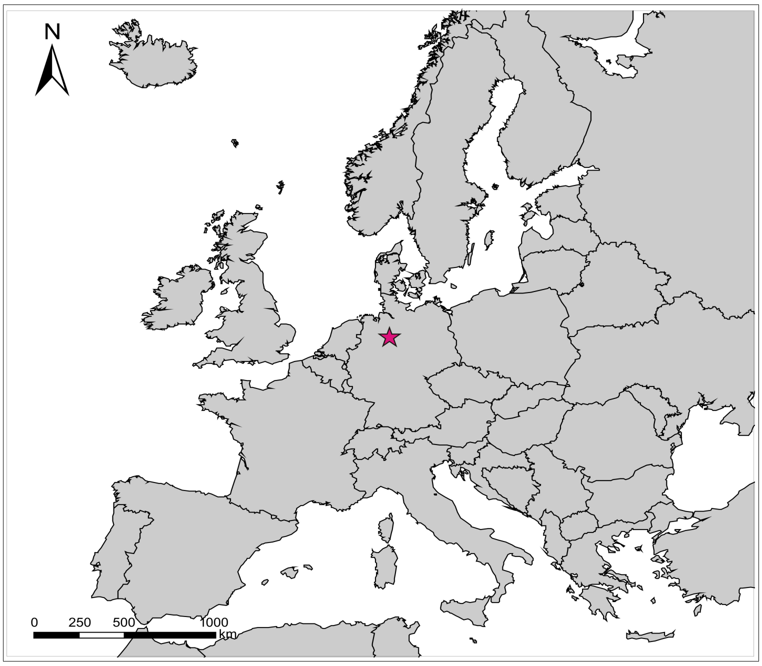

Figure 1: Location of the study site TOMO_south, indicated by a star.

Due to peat mining and the uncovering of such stump layers, areal dendrochronological investigation became possible. The trees dated absolutely by dendrochronology deliver the finest temporal reconstruction of bog expansion and local bog formation, particularly by their dying-off dates (Eckstein et al., 2009, 2010; Edvardsson et al., 2014, 2016; Krąpiec et al., 2016; Leuschner et al., 2002, 2007). Eckstein et al. (2009, 2010, 2011) have shown that the tree dying-off occurs in phases, which are often synchronous in different mires. They were able to show that the tree dying-off is mostly due to hydrological changes, while fire and storm have been found to be of little relevance on the investigated sites. Particularly the observed synchrony of pine establishment and dying-off phases in different mires shows that the local mire development documented by the trees is strongly linked to climatic variations (Eckstein et al., 2009, 2010, 2011; Edvardsson et al., 2012a, b).

Figure 2: View of site TOMO_south. The upper layers of peat have been removed. Numerous tree stumps are protruding. Photo: Inke Achterberg.

The phase-wise advance of a raised bog in northwest Germany is particularly well documented in the mire “Totes Moor” at the site TOMO_south (Fig. 1). At the site, tree remains from one stratigraphical stump-layer (Fig. 2) turned out to originate from four millennia, documenting the bog progress across some 500 m.

At site TOMO_south, the spatial as well as the temporal distribution of many preserved trees has been obtained. The present study aims to connect areal changes to the temporal patterns observed.

2. Material and methods

The Totes Moor mire complex is located north of the Steinhuder Meer, a lake near Hanover. The undulating relief below the mire consists of sand and is likely to have held several small ponds and isolated mires before the expanding mire complex connected them. The whole depression of the lake is based on the same nutrient-poor glaciofluvial deposits (mostly sand) that characterize the geest region.

On the site TOMO_south many in situ tree stumps as well as in situ stems and ex situ stumps (pulled during ditch digging and left at the ditch side) were sampled as radial slices using a chainsaw. The tree remains were documented by using a feature table (regarding their growth, size, conservation condition etc.), photographic pictures and GPS coordinates. On some tree stumps, the root depth and shape were investigated. Later, the samples were dried, reduced by circular saw, and frozen. Then, suitable measuring radii were surface-cut by scalpel, contrasted by rubbed-in chalk dust and measured on an Aniol motorized measuring device with CATRAS measuring software to a precision of 0.01 mm. The tree-ringwidth series were cross-dated using mainly the V-program set (EXTRACT, HEADER, SUMMORY, SYNCH2, VFORMAT, vshow, VSORT) by Thomas Riemer (Riemer, 1994, and unpublished work) and the TSAPWin program by Rinntech (Rinn, 2003). The Lower Saxony chronologies of oak and pine were used as a base for dating. Part of the Lower Saxony Pine Chronology is also a product of this work. For the floating chronology segment three radiocarbon dates, which were determined at the Leibniz Institute for Applied Geophysics (LIAG) in Hanover, were wiggle-matched on the base of the IntCal13 calibration curve (Reimer et al., 2013) using the OxCal 4.2 online software (Bronk Ramsey et al., 2001; Bronk Ramsey, 2009).

In situ finds were later separated from ex situ finds. For the spatio-temporal reconstruction of raised bog development (Fig. 5), stumps with root plates partially dragged upward, which retained part of their root system within the grown peat and thus their location, were used along with the finds that were in situ in the stricter sense. Up to 96 trees have possibly been moved in such a way. They were added to the 116 trees which were considered “in situ” in a stricter sense. In total 210 tree stumps with dendrochronological datings and 2 radiocarbon-dated tree stumps are included in the reconstruction and displayed (Figs. 5 and 6). All 212 are referred to as “in situ” in the following. All maps were created using ArcGIS 9 and 10 (Esri) mapping software. Figures were prepared using CoralDRAW software.

In addition, the peat stratigraphy of 56 cores at the site was investigated macroscopically. Elevations a.s.l. were determined by stadia survey for 36 of the peat cores taken for this study, and for 63 on behalf of ASB-Humus peat mining company, who kindly shared their data. The elevation a.s.l. of the mineral base (sand) beneath the peat is depicted as a regularized spline interpolation on the base of the total 99 elevation measurements (Fig. 6).

Dendrochronological dates are given in years BC and radiocarbon dates in years cal BC. Labelled time spans, like chronology segments or gaps, always include the years named.

3. Results

At the site TOMO_south, a rather levelled field left by peat mining revealed the remains of an apparent pine forest (Fig. 2). A closer look revealed that what had appeared to be one continuous tree layer actually did contain neighbouring stumps grown on slightly different elevation levels (Fig. 3).

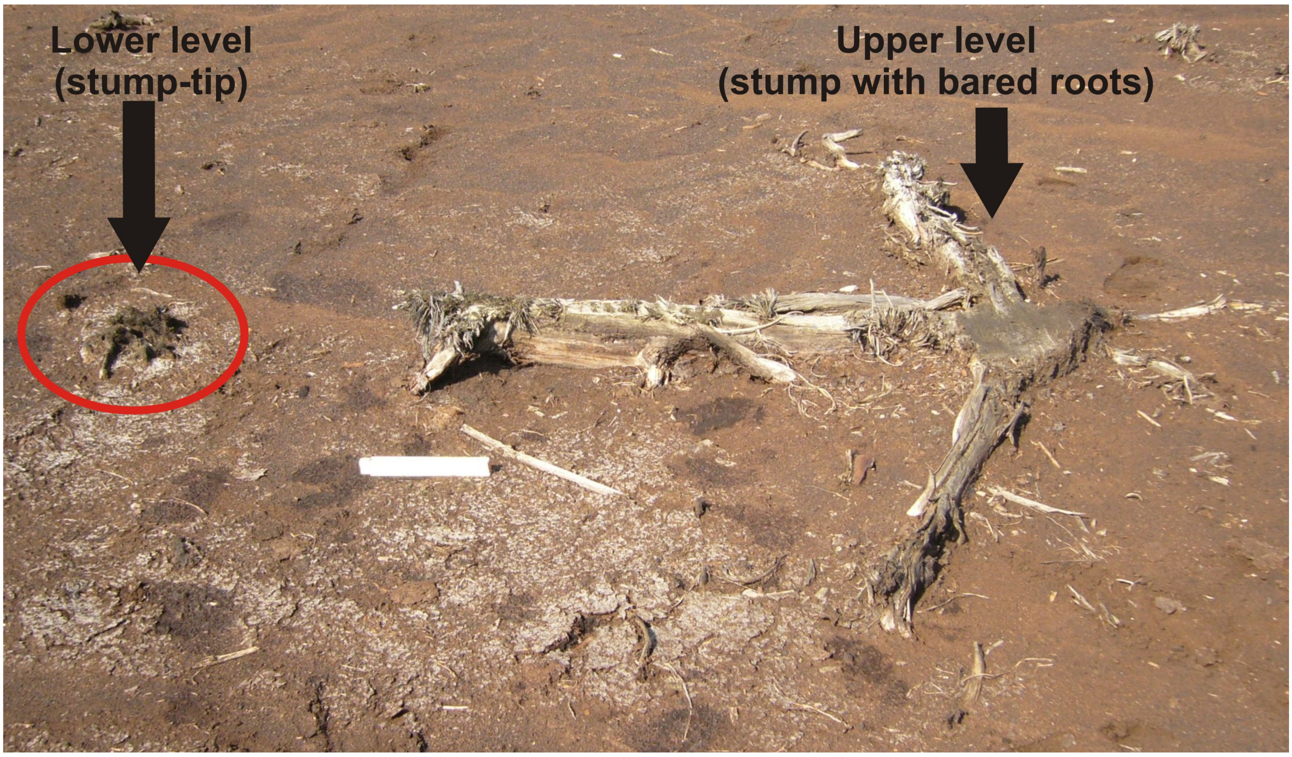

Figure 3: Tree stumps at site TOMO_south grown on two elevation levels. The upper level trees are sometimes supported by their dead successors. Photo: Inke Achterberg.

Of the 700 tree stumps sampled at this site most were pine (Pinus sylvestris), only 10 oak (Quercus sp.) stumps were sighted and sampled. The pine remains often had retained bark in the lower parts, often being preserved to bark edge or showing only minimal decay at the outermost rings.

3.1. Temporal distribution of the trees

Only after many pine stumps had been sampled (a first sampling of about 70 trees did not provide good crossdating results) was dendrochronological dating successful for 477 trees. An additional floating chronology segment of 30 trees was radiocarbon-dated. The trees at the seemingly homogeneous site in fact originated from various centuries (Fig. 4, Table 1). They grew around 7000 ± 80 to 6700 ± 80 cal BC (floating chronology segment, wigglematched C14 date) and between 6703 and 3403 BC (dendrochronological calendar dates). The floating chronology segment covers 309 years, while the chronology segments with dendrochronological calendar dates cover 2345 years.

The majority of the trees (443) originate from the 7th to 5th millennia BC. Much fewer trees (34) represent the 4th millennium BC. Tree occurrence was not scattered over time but is found to cluster in at least eight groups (chronology segments C14 and A1–F, Fig. 4). There are also periods without pine trees preserved at the site: while the two shortest of the five gaps between the site chronologies (6 and 11 years in length) belong to the poorly replicated 4th millennium BC and are likely due to sampling design (which, in this case, is the placing of the site borderline through peat mining), the longer gaps between the well-replicated chronologies likely reflect the actual dynamic at the site. There are periods where tree establishment and tree dying-off events appear rather scattered (e.g. 6000–5800 or 5230–5120 BC), and intervals where the wooded phases display rather clustered tree establishment and tree dying-off. Particularly clear are the dying-off events around 6315, 5060 and 3838 BC (Fig. 4).

Rejuvenation pulses, where several trees germinate within a few years, are found within several segments. This can be seen clearly in segments C14, A2 (repeatedly) and B. Segments C and E depict the same, but less clearly. Segment F, consisting of only five trees, is too poorly replicated to evaluate patterns. Segment A1 does not show the described pattern. Neither does segment D, but it is also poorly replicated, consisting of only 10 trees. A closer look reveals that all rejuvenation pulses within segments are preceded by a time of limited or even missing rejuvenation. The rejuvenation pulses hence seem to mark the end of periods with limited tree establishment. In several cases the phases of limited tree establishment are also phases of frequent tree dying-off. This is particularly clear for the germination pulse beginning with the dying-off event around 6315 BC.

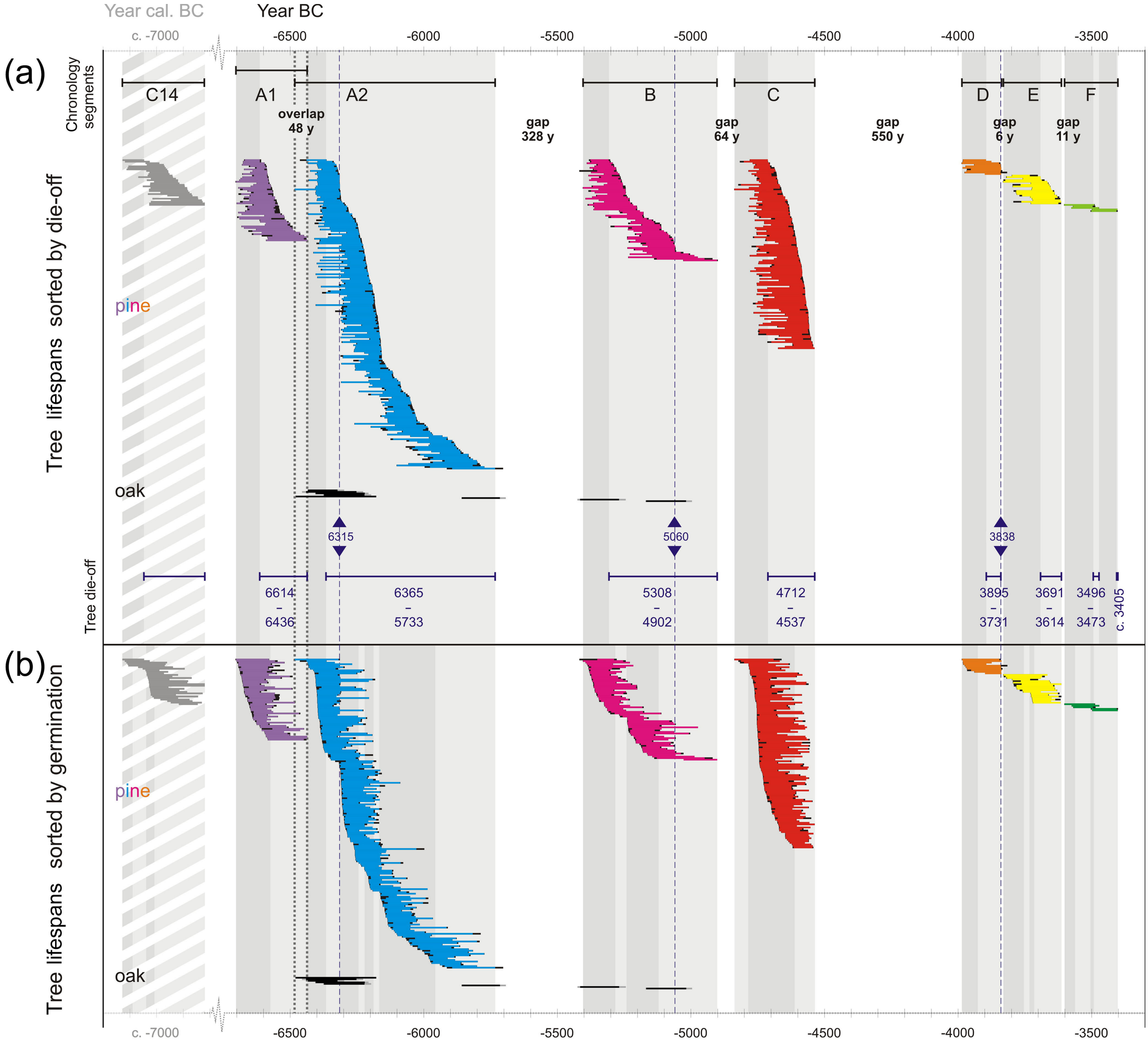

Figure 4: Temporal distribution of pine trees at site TOMO_south. On top the chronology segments C14 and A1-F are indicated. The gaps between the site chronology segments (white) are labelled with their duration. The time covered by the site chronologies of TOMO_south is underlain in grey, and that for the floating chronology segment C14 striped in grey-white. The coloured horizontal lines indicate the lifespans of the individual dated trees from the site (measured rings coloured, estimated missing rings black). The trees of each chronology segment (Table 1) are shown in a different colour (A1: dark violet; A2: blue; B: pink; C: red; D: orange; E: yellow; F: green), the floating chronology segment C14 in grey. The colours are used accordingly in the spatial mapping (Figs. 5 and 6). The oaks from the site are displayed in black, below the pines. In (a) the trees are sorted by dying-off date. The three most prominent events of cumulative tree dying-off are highlighted by a dashed blue vertical line and labelled by year BC. Below, the periods from first to last tree dying-off (last measured ring) are indicated, labelled by years BC. The lighter grey backgrounds indicate when the trees of a chronology segment start to die off. In (b) the trees are sorted by germination date. Here, the lighter grey backgrounds indicate periods with limited tree establishment.

Table 1: Chronology cover. For this table, only the measured rings were used, and estimations of missing rings to pith or bark were not added. Only the trees with dendrochronological calendar dates are listed below.

Chronology segment name	A		B	C	D	E	F	total
	A1	A2						
Color	Dark violet	Blue	Pink	Red	Orange	Yellow	Green	
Chronology cover [yr BC]	6703 – 5733		5404 – 4902	4837 – 4537	3986 – 3838	3831 – 3614	3602 – 3403	Dispersed over 3301 years
	6703 – 6436	6483 – 5733						
Tree dying-off [yr BC]	6614 – 6436	6365 – 5733	5308 – 4902	4712 – 4537	3895 – 3838	3691 – 3614	3496 – 3473 3407 – 3403	1482 years
Chronology segment length [years]	971		504	301	149	218	202	2345 years
	268	752						
Chronology gap [years]	-	328	64	550	6	11	-	959 years
Replication [trees]	254		66	123	10	19	5	477 trees
	53	201						

3.2. Reconstructed bog expansion

Mapping of the dated in situ trees generally shows groups of contemporaneous trees growing together. The oldest trees, from the early 7th millennium BC, cluster in the south-east of the plot, while the youngest, those of the 4th millennium BC, are found to the north-west, with the rest arranged in between. This clearly shows the general direction of raised bog expansion from south-west to north-east across the plot, even though there are some discontinuities within the site. Firstly, the groups of trees are not arranged in orderly stripes (Fig. 5) but form tongues and islands, often in correspondence to the dynamics of the mineral base (sand) beneath (Fig. 6). On sandy elevations trees persisted much longer, while the surrounding mire had long become a treeless raised bog (Fig. 7). Secondly, there are sometimes individual trees from one time interspersed into a group from another.

The mineral base is lowest to the south-east, where the oldest trees were found. Those trees document the oldest part of raised bog in the plot.

In Fig. 5 the raised bog advance has been reconstructed according to the dated in situ tree remains. The interpolated areas (Fig. 5) were set in a “no tree growth after” approach. That is, in places where trees from different chronology segments occur intertwined, the place was assigned to the younger specimen.

This was done in an attempt to depict the advance of the raised bog, which, in its final state, is mostly treeless (Ellenberg, 1996).

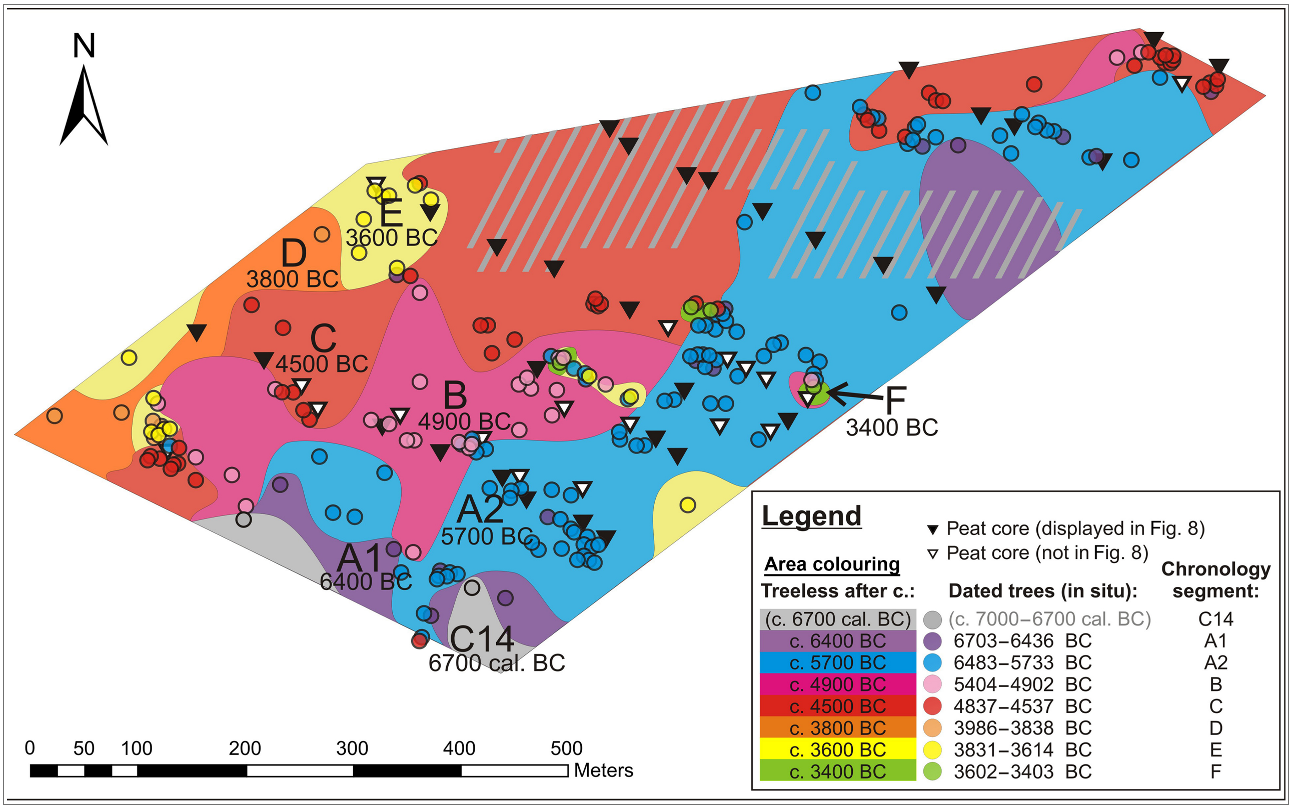

Figure 5: Reconstructed raised bog advance in terms of "no more tree growth". The coloured dots indicate in situ tree remains, while their colour indicates the chronology segments they belong to. The hachures indicate areas with a lack of dated in situ samples. The coloured areas show where no more trees grew at a certain period. In this sense, the oldest section is where only trees of the floating, radiocarbon-dated segment C14 (beginning of the 7th millennium cal BC) were found, which is coloured grey. The dark violet areas show where no trees younger than the first group of trees with dendrochronological calendar dates, A1 (early 7th millennium BC), were found. Blue areas feature only trees from the late 7th and early 6th millennium BC (A2) and older. The pink area delivered trees from the second half of the 6th millennium BC and the beginning of the 5th (B). The red area shows where no trees grew after the first half of the 5th millennium BC (C). The orange indicates where, after that, only trees from 4000–3800BC (D) were found. The yellow area still featured trees in the first half of the 4th millennium BC (E), and the green in the second half of the 4th millennium BC (F). The colours with the corresponding dates are given to the right.

3.3. Peat stratigraphy

The peat stratigraphy is shown for 31 cores of the site (Fig. 8), displayed in elevational relation. In total, elevation a.s.l. has been determined for 36 of the 56 cores which were peat-stratigraphically investigated at the site. Please note that some cores have been taken at the edge of the peat excavation field, where peat was left standing more than 1.5m higher than the level of the tree stump layer.

The general order above the glacial sand deposits is the following: brown moss peat on bottom, wood-rich peat above, followed by Sphagnum peat on top. The pine tree remains are found at the fen–bog transition. This picture is rather continuous over the site, with differences mostly restricted to layer thickness.

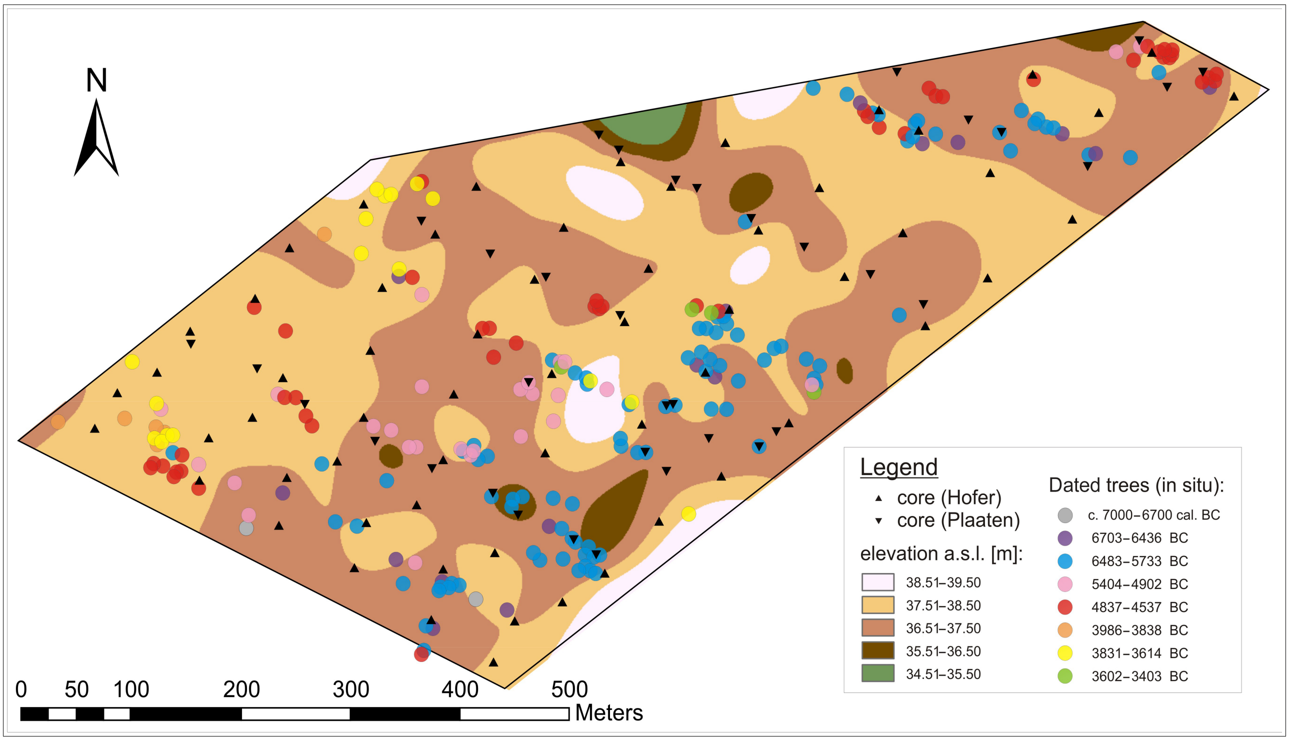

Figure 6: Elevations a.s.l. of the mineral base (sand) below the peat. Regularized spline interpolation of 99 measurements. The elevations are interpolated using a regularized spline. The actual measurements range from 36.42 to 38.16ma.s.l.; therefore, the first and the last elevation class (green, below 35.50ma.s.l., and white, above 38.51ma.s.l.) are products of extrapolation only. The coring points are indicated by triangles. The dated in situ trees are shown as circles, for each chronology segment (Table 1) in a different colour (C14: grey; A1: dark violet; A2: blue; B: pink; C: red; D: orange; E: yellow; F: green).

Figure 7: Pine growth at a bog site in Finland. View across a stretch of treeless bog. In front are small trees, thinning out where the peat deepens. In the back large trees form a wooded "island" where the mineral ground ascends. Photo: Inke Achterberg.

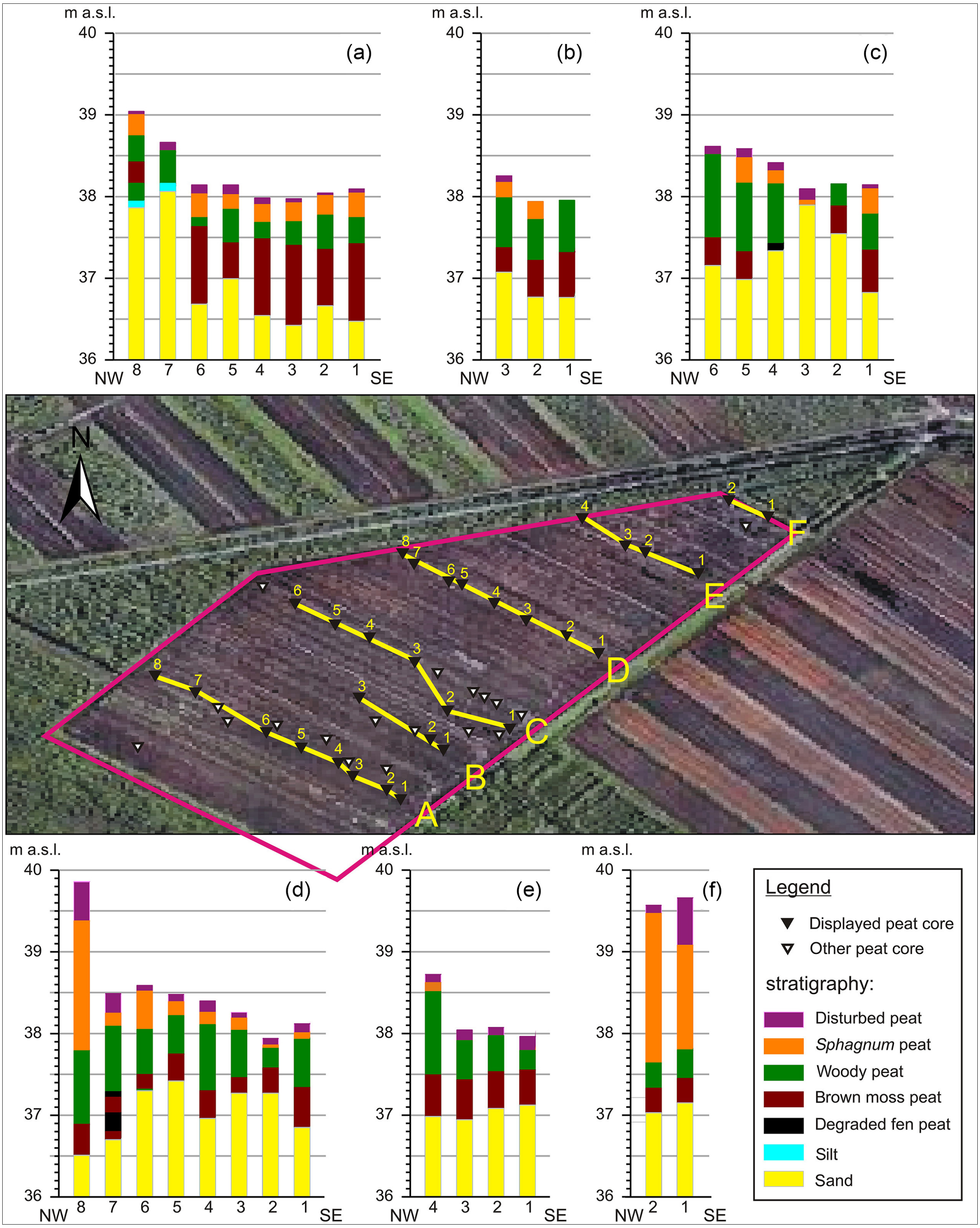

Figure 8: Peat stratigraphy. Six transects are shown with the peat stratigraphy and elevation a.s.l. of the cores. In the aerial view, site TOMO_south is outlined in pink. The locations of the displayed peat cores are indicated by black triangles, yellow lines connecting the transects. Peat stratigraphy for cores without elevation measurement is not shown. Please note that cores D8, F1 and F2 were taken at the border to the plot, where peat was left standing significantly higher than within the plot, where the tree layer was exposed. Underlying satellite image: ©2008 Google Earth, image ©2009 Geo Content, ©2009 Tele Atlas.

The brown moss peat is mostly weakly humified, often featuring Menyanthes seeds (Menyanthes trifoliata) in the middle or upper part and silt near the bottom. The wood-rich peat varies, mostly being more strongly humified, but containing various portions of Betula (bark), Alnus (wood), Pinus (bark and cone) and charcoal in different spots and layers.

A few spots feature an Eriophorum layer (Eriophorum vaginatum) below the Sphagnum peat. More cores show some Eriophorum mixed in with the lower Sphagnum peat or the upper wood-rich peat. The Sphagnum peat, where distinguishable, consists of Sphagnum section Acutifolia peat, Sphagnum section Cuspidata peat and Sphagnum–Carex peat.

A few of the cores (two of the ones shown) feature highly humified fen peat in the lower part, which is likely to be brown moss peat in a decomposed state. In agreement with this assumption, the brown moss peat of most cores is more humified at its base.

3.4. Root morphology

There is one main feature dividing the pines into two groups by their roots: the first type of root systems (type 1) spreads out horizontally, without any downward pointing roots. The central root at these trees has either died off at a length of about 10 cm or less or is not traceable at all. The second type of root systems (type 2), however, displays downward growing roots, most of them with a pronounced central root that has grown vertically downwards. Most often, these reach 20 to 40 cm below the root plate.

These two types clearly show up in the ex situ material pulled from the ditches. Roots below the stem were investigated also for 18 in situ stumps (Fig. 9), primarily to clarify if their roots reached the mineral soil below the peat. This was not the case with the examined specimen.

Figure 9: Strong downward roots below a tree stump at TOMO_south (tree life 5396–5230 BC, chronology segment B). Photo: Inke Achterberg.

4. Discussion

4.1. The preserved trees

During dry periods, with consequently lowered bog water tables, pine forestation can temporally also occur on the bog. Such growth of large pines within raised bog (rooting in Sphagnum peat) was described by, among others, Overbeck (1954) for a mire in northern Germany, by Moir et al. (2010) for such findings in Scotland, by Edvardsson et al. (2014) in southern Sweden, or in general terms by Ellenberg (1996).

However, this is not the case at TOMO_south, where the pines occur at the fen–bog transition and not within Sphagnum peat layers. As confirmed by peat stratigraphy, the tree remains in TOMO_south represent a persistent pine forestation at the raised bog margin. Pine forestation at raised bog margins is a very typical occurrence. The pines colonize marginal parts of the bog, where the ascending bog surface is well drained compared to more central parts (Ellenberg, 1996; Overbeck, 1975).

The death and conservation of the trees, however, appears to be closely connected to the expansion of the raised bog and the rise of the corresponding water table. This has been found evident on base of abundant upward growing roots late in the tree's life, the drastically narrowing rings near the bark, peat stratigraphical context and the state of conservation at various comparable sites investigated in northwest Germany and southern Sweden (Eckstein et al., 2009, 2010; Edvardsson et al., 2012b, 2014; Leuschner et al., 2002, 2007). Therefore the death of the trees and their conservation under Sphagnum peat dates raised bog expansion, and using in situ stumps adds location to the event. As the site is densely covered with tree stumps (rather throughout), we assume that all significant and lasting raised bog expansion should be documented by embedded trees.

The tree data display phases of cumulative dying-off on the one hand and gaps between site chronologies on the other. This documents phases of the bog expanding, and phases without significant expansion at the site.

the disconnection of the fen peat surface from the lowered ground water and its nutrient supply The phases of bog expansion should generally relate to relatively humid climate phases, as the bogs are dependent on rainwater (Ellenberg, 1996). Raised bog formation can be favoured by a preceding lowering of the water table through (Hughes, 2004; Tahvanainen, 2011; von Bülow, 1935). At site TOMO_south this combination of a drier phase with lowered water tables followed by a phase of swift raised bog expansion may have occurred repeatedly. A lowered water table is documented by numerous tree stumps with vertical roots (type 2). These roots often reach 20 to 40 cm below the root plate, and include a thick central root going straight down (Fig. 9). Root system type 1, however, being spread out flat and without any pronounced vertical root, is also common at the site. Such roots indicate a higher water table, limiting rooting space at the time of growth. This shows that not all of the trees embedded by the expanding raised bog grew under drier conditions with significantly lowered water tables.

In general, tree growth on a mire can also contribute to a lower water table, as transpiration is being increased (Moir et al., 2010; Limpens et al. 2014). This effect can be reversed, however, where shading in high-density stands reduces evaporation even more and thus results in increased surface wetness (Limpens et al., 2014).

The area around the bog appears to have been wooded continuously, as pollen records from the bog itself (Shumilovskikh et al., 2015; Schlütz unpublished) and the regional landscape history (Behre, 2008) suggest. The trees from these surrounding mineral soils would not be preserved, however.

4.2. Dying-off phases

Most indicative for periods of lateral bog growth are those of tree dying-off. As there are seven dendrochronologically dated chronology segments, there are at least seven such periods (Fig. 4). Particularly for the chronology segments A2 and B, phases of accelerated and decelerated bog advance appear to be depicted in the trees. Even though this could partially also relate to the irregular sampling pattern, some prominent short-term events of cumulative tree dying-off, like those around 6315, 5060 and 3838 BC, are clear. The periods in which the trees died off are 6614–6436, 6365–5733, 5308–4902, 4712–4537, 3895–3838, 3691–3614, 3496–3473 and 3407–3403 BC (Fig. 4, Table 1). These are interpreted as phases of raised bog expansion, which in turn imply moist phases. How the trees are successively affected by the local raised bog development is also illustrated in the individual tree ring series, as shown for segment F (Fig. 10).

The floating chronology segment C14 shows subsequent dying-off approximately. The trees of segment C14 are less well preserved. This might indicate a mire environment at the time with higher microbial activity, possibly with less continuous water logging of the mire surface.

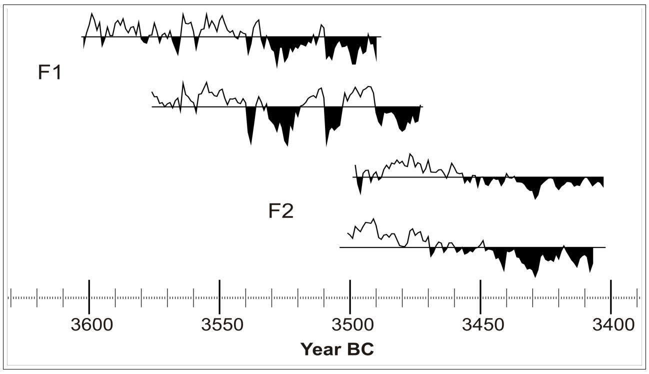

Figure 10: Tree-ring-width curves of chronology segment F. The mean value of the tree ring widths is indicated by a horizontal line for each curve; the area below mean is filled black to highlight growth depressions. One sample is not shown because it is missing several rings to bark and therefore the record of the final years of that tree's life. All trees show narrow ring widths prior to their deaths. These growth depressions are not reflected equally in the surviving trees. This illustrates the locality of the calamity.

4.3. Rejuvenation pulses and suppression

The rejuvenation discussed here is limited to trees which grew up to form a number of rings sufficient for dendrochronological dating.

In the course of dying-off phases, rejuvenation is often missing. When all trees of stand are killed by a fatal influence, young trees germinated shortly prior to the event would not occur in the dendrochronological record due to insufficient tree ring numbers for dating. This can not be more than part of an explanation, however, since the dying-off phases are in many cases stretched longer than the lengths of time required of a tree ring sequence for dating.

The moist conditions relating to the dying-off phases, however, would likely also suppress successful tree establishment. Holmgren et al. (2015) found Pinus sylvestris recruitment on bogs to be more successful on drier sites (hummocks) with lower water tables. They found natural seedling establishment to occur on both moist (lawns) and drier microsites (hummocks) equally. Young trees, however, were much less abundant on the moister sites (lawns), and adult trees were only found on the drier sites (hummocks) with lower water tables (Holmgren et al., 2015).

Several times in the record, numerous germinations occur synchronous. These are mostly found following a phase (mostly of one to a few decades) of suppressed rejuvenation. Hence, they most likely mark the end of the unfavourable conditions which suppressed rejuvenation. Drier conditions on the peat surface are likely a factor. Furthermore, the large numbers of simultaneous seedling establishment can be explained by the lack of shading undergrowth as a preceding generation of young trees is missing.

Tree rejuvenation events (germination phases), which took place simultaneously in several different peat bogs, sometimes coincide with dying-off events, and more often follow directly after them. Eckstein et al. (2010, 2012) and Leuschner et al. (2007) have referred to this as germination–dying-off phases (GDOs). Even though a spatial pilot study (Stenzel, 2013) did not find the newly established trees directly in the area shaded by those trees which had just died off, the mechanism causing the coherence is still suspected to be driven by competition for light. Other trees and shrub (e.g. Betula or young pine trees) would have suffered from the same influence which killed the large pine trees and thereby created an opening in the canopy. This could explain the coherence or close succession of dying-off and germination phases.

Zackrisson et al. (1995) also take seed production into account to explain rejuvenation pulses in pine populations. Conditions stressful to the trees can enhance seed production. However, favourable climate conditions may also influence seed production. Enhanced seed production under stressful conditions supports rejuvenation when the older tree generation is about to die off. The germination and establishment of these seedlings, however, depends on the opening of canopy created by the tree dying-off, and on otherwise suitable conditions at the site. Therefore, it is unclear how far seed production might be reflected in tree establishment at the given site.

4.4. Chronology gaps

The site chronologies of TOMO_south are interrupted by five gaps, ranging between 550 and 6 years in length (Table 1).

The two very short gaps (6 and 11 years respectively) are rather insignificant, especially since the respective period is not well replicated. These gaps are likely to result from sampling design, as the neighbouring chronology segments are poorly replicated and the according trees are found on the rim of the investigated area. It is well possible that more trees represent that period but that they were located just outside the margin of the site to the north-west. Both short gaps are from the 4th millennium BC (3837–3832 (6 years) and 4613–3603 BC (11 years)) (Table 1), when trees only grew at the site on sandy elevations, forming wooded "islands" in the mire (Figs. 5, 6 and 7).

The three longer gaps are more meaningful. The two very long gaps are 5732–5405 (328 years) and 4536–3987 BC (550 years), the gap of intermediate length (64 years) is 4901–4836 BC. All three are framed by well-replicated site chronology segments, with the respective trees found well within the site. Given the dense sampling of the site, it can be assumed that the large gaps actually represent periods with no or very few pine trees being embedded at the site.

Other studies have attributed chronology gaps in raised bogs to a lack of tree growth due to high surface wetness. This makes much sense for the tree layers well within Sphagnum peat as described, for example, in Scotland (Moir et al., 2010) and south Sweden (Edvardsson et al., 2014). At those sites, tree growth was only possible on the raised bog during drier phases.

In the case of the present study, however, the stratigraphic position of the tree layer is at the fen–bog transition. Apparently, at TOMO_south the expanding raised bog embedded trees grown at its rim. The site was thoroughly covered with pine stumps. These were representatively sampled and dated. Taken together, this suggests that the large chronology gaps at TOMO_south represent periods of (near) stagnation of the lateral raised bog growth. Therefore the gaps are not interpreted as periods of particularly high surface wetness in this case but instead the reverse. Instead, during the periods of site chronology gaps the raised bog at TOMO_south appears not to have expanded significantly. Lacking bog expansion can be related to relatively dry phases. There are, however, tree dying-off phases documented at other bogs in northwest Germany within the time of these gaps. In particular, in the 550-year gap at TOMO_south (4536–3987 BC), there are two pronounced dying-off phases (ca. 4490–4370 and 4230–4170 BC) within and one at the end of the gap (ca. 4010–3960 BC) in other bogs (Achterberg et al., 2015). Therefore, these phases of apparent bog growth stagnation at

TOMO_south can not be related to climatic dry phases directly.

4.5. Spatial distribution

The mapping of the dated in situ trees at the site (Fig. 5) shows the raised bog expansion from south-east to northwest. The mineral base is lowest in the south-east of the plot and highest to the south-west of the plot, as well as in the centre of the site (Fig. 6). This direction is parallel to the nearest lake shore.

There are clear spatial clusters of trees from the same periods, which usually border to patches of the preceding and following chronology segments. This is coherent with the picture of the advancing raised bog successively embedding the tree stumps.

The oldest parts (with trees only from the first chronology segments) are found to the south-east, where the mineral base is low. The trees from more recent centuries were found in places were the mineral base ascends, like the sandy elevation near the centre of the plot. Wooded islands within the raised bog apparently persisted for a long time (Figs. 5, 6 and 7). The distribution of trees from different chronology segments in the plot can mostly be related to the dynamic relief of the mineral base (Fig. 6).

At some places, however, there are also trees from different epochs interspersed (Fig. 5). In the mapping of raised bog expansion (Fig. 5) these places are assigned to the last tree dying-off they document, as the advancing central part of the bog should have been generally treeless (Ellenberg, 1996). Re-establishment of trees in places where trees had already been embedded before may have been favoured by drier conditions, or simply related to the dynamic relief, with the root plates of previous generations additionally serving as “stepping stones” for the new trees to grow on.

4.6. Peat stratigraphy

Thick and mostly weakly humified layers of brown moss peat were found at the bottom of TOMO_south peat cores. It was the base for extended tree growth, which then itself deposited thick layers of wood-rich peat. Where basal swamp forest peat is less humified, the brown moss can still be seen intertwined. Likewise intertwined is the first Sphagnum growth into the top layers of pine-rich peat. This depicts a succession to ombrotrophy, with one plant community creating the habitat for the next.

There are fine mineral materials found interspersed in several peat cores and layers. These may have been washed into the moss by temporary flooding or, particularly in the older deposits, also might have been blown into the mire.

4.7. Climatic comparisons

The following alignments were largely limited to records which have a certain precision of dating (dendrochronological, varve, etc.), are located with some level of proximity (European studies), regard the time frame covered by TOMO_south trees and also describe a hydrological signal. For the type of proxy used in the studies referred to and their location, please see Table 2. The temporal overview given in the following text is also displayed in Fig. 11a and b.

We interpret the dying-off phases as times of lateral mire expansion. Bog expansion again would require a certain humidity, which may be more dependent on a reduced evapotranspiration than the actual precipitation alone. This would mean the dying-off phases in the periods ca. 6600–6450, 6350–5750, 5300–4900, 4700–4550, 3900–3850, 3700–3600, and 3500–3400 BC indicate more humid phases. In turn, the gaps between the site chronologies and the periods of rather undisturbed tree growth are interpreted as phases of stagnation of lateral raised bog expansion. These may be related to climatic conditions unfavourable for mire growths, possibly involving drier periods. This would apply to the phases of ca. 6450–6350, 5750–5300, 4900–4700, 4550–3900, 3850–3700, and 3600–3500 BC.

As mentioned before, the dying-off phases observed at TOMO_south show much synchronism with dying-off phases observed at other mire sites in northwest Germany (Eckstein et al., 2009, 2010, 2011), which emphasizes their climatic context. In addition to the temporal placing of the TOMO_south record (terminating 3400 BC) and its location in the northwest German lowland, where settlements were established later than on the richer soils of the adjacent hills, this synchrony makes it appear unlikely that anthropogenic clearance activity in the catchment area might have had a detectable influence on the bog's hydrology.

The replication of the northwest German dendrochronological pine record, even though it is influenced by sampling patterns and the accessibility of trees depending on peat mining, also reflects climate. This shows in the European similarities of chronology replication (Edvardsson et al., 2016). In addition, it is also illustrated by the comparison with other climate-related records (Fig. 11a). The number of dates for lowered and raised lake levels in central Europe (Magny et al., 2004) displays similarities with the replication of the northwest German pine chronology. The northwest German pine declines (die-off phases visible in replication) within the long TOMO_south gap (ca. 4500–4000 BC) fit phases of higher lake levels in the data of Magny et al. (2004) particularly well (Fig. 11a). The replication at TOMO_south is largely in tune with the overall pine replication record of northwest Germany, except for northwest German phases of pine growth which are not represented at TOMO_south, dating ca. 4900–4800 and ca. 4500–4000 BC (which is

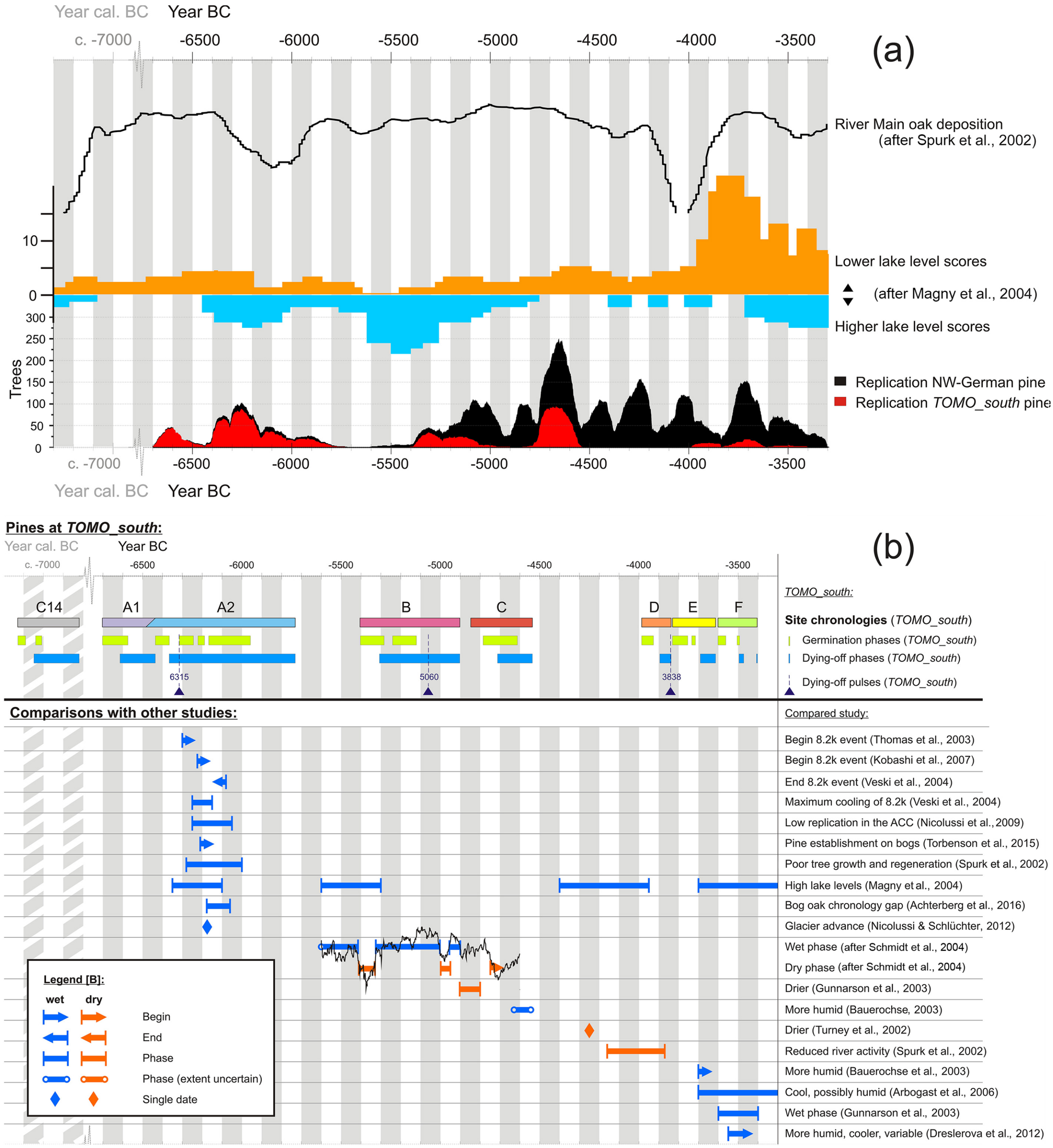

Figure 11: (a) Comparison of the replication of TOMO_south northwest German pine chronologies with other climate-related records.

From top to bottom: oak deposition at the river Main (Spurk et al., 2002); scores of higher and lower lake levels in central Europe (Magny et al., 2004); replication of the northwest German pine chronology including the pines of TOMO_south, which are highlighted in red. (b) Comparison of the phases observed at TOMO_south with those of other studies.

Table 2: Comparisons with other palaeoenvironmental studies

Publication	Proxy	Location	Time	Indication	TOMO_south	Fit
Thomas et al. (2007)	Ice core chemistry and stable isotope	Greenland	Beginning ca. 6300 cal BC	Cooling	Dying-off phase ca. 6350–5750 BC; strong dying-off pulse at ca. 6315 BC	+
Spurk et al. (2002)	Dendrochronological	Western Germany	ca. 6270–6000 BC	Poor growth and regeneration conditions	Frequent tree dying-off from 6250 to 6157 BC	+
Kobashi et al. (2007)	Ice core (GISP2) methane and nitrogen isotopes	Greenland	Beginning ca. 6225 cal BC	Cooling	Frequent tree dying-off from 6250 BC to 6157 BC	+
Torbenson et al. (2015)	Dendrochronological; pine establishment at three bog sites	Ireland	From 6210 BC on		Frequent tree dying-off from 6250 to 6157 BC	+
Veski et al. (2004)	Varve	Estonia	6250–6150 varve years BC	Maximum cooling	Frequent tree dying-off from 6250 to 6157 BC	+
Nicolussi et al. (2009)	Dendrochronological	Alps	ca. 6250–6050 BC	Low replication	Frequent tree dying-off from 6250 to 6157 BC	+
Veski et al. (2004)	Varve	Estonia	6080 varve years BC	Abrupt end of the 8.2 ka cooling period		
Achterberg et al. (2016)	Dendrochronological	Northwest Germany	6177–6060 BC	Gap in bog oak chronology		
Nicolussi and Schlüchter (2012)	Dendrochronological	Alps	ca. 6175 BC	Glacier advance	Frequent tree dying-off from 6250 to 6157 BC	+
Magny (2004)	Radiocarbon, dendrochronological and archaeological dates	France and Switzerland	ca. 6350–6100 cal BC	High lake levels (I)	Start is beginning of the dying-off phase of segment A2 at TOMO_south (6365 BC)	+
Magny (2004)	Radiocarbon, dendrochronological and archaeological dates	France and Switzerland	ca. 5600–5300 cal BC	High lake levels (II)	End coincides with beginning of dying-off phase (5308–4902 BC)	+/–
Schmidt et al. (2004)	Dendrochronological	Western Germany	before 5600 (TAQ)–5420 BC	More or less humid	Long gap (5732–5405 BC)	–
Schmidt et al. (2004)	Dendrochronological	Western Germany	ca. 5410–5330 BC	Dry phase	Tree establishment and growth (no dying-off)	+
Schmidt et al. (2004)	Dendrochronological	Western Germany	ca. 5320–5000 BC	Wet phase	Beginning at the same time as dying-off phase ca. 5300–4900 BC begins	+
Schmidt et al. (2004)	Dendrochronological	Western Germany	ca. 5000–4950 BC	Dry phase	(Not reflected clearly in the data of TOMO_south)	–
Schmidt et al. (2004)	Dendrochronological	Western Germany	ca. 4950–4900 BC	Wet phase	End at the same time as dying-off phase ca. 5300–4900 BC ends	+
Gunnarson et al. (2003)	Dendrochronological	Sweden	ca. 4900–4800 BC	Drier conditions	Found accordingly for TOMO_south (ca. 4900–4700 BC)	+
Bauerochse (2003)	Palynological implications, context of dendro-dated find	NW Germany	Context of find dated to 4629–4545 BC	More humid conditions	dying-off phase 4712–4537 BC	+
Magny (2004)	Radiocarbon, dendrochronological and archaeological dates	France and Switzerland	ca. 4400–3950 cal BC	High lake levels (III)	Gap between the site chronology segments (ca. 4500–3900 BC)	–
Turney et al. (2006)	Dendrochronological	Ireland	ca. 4250 BC	Drier conditions	Within the site chronology gap 4536–3987 BC	+
Spurk et al. (2002)	Dendrochronological	Western Germany	ca. 4160–3870 BC	Reduced activity of the river Main	Gap 4536–3987 BC, which might point towards drier conditions as well; dying-off phase at TOMO_south from 3895 BC on, 25 years prior to the end of the period identified by Spurk et al. (2002)	+/–
Bauerochse (2003)	Palynological implications, context of dendro-dated find	NW Germany	After 3701 BC	More humid conditions	Dying-off phase at TOMO_south from 3691 to 3614 BC	+
Arbogast et al. (2006)	Dendrochronological dates from archaeological layers	Swiss Alps, French and German	3700–3250 BC	Lake level rise; climatic deterioration, cool and possibly humid conditions	Beginning dying-off phase segment E (3691 BC), (covers dying-off phases segments E and F)	+
Magny (2004)	Radiocarbon, dendrochronological and archaeological dates	France and Switzerland	ca. 3700–3250 cal BC, maximum 3350–3250 cal BC	High lake levels (IV)	Start is beginning of dying-off phase segment E (3691 BC)	+
Dreslerova (2012)	Multi-proxy (review)	Europe (multi-site)	ca. 3550 cal BC	Pronounced shift towards wetter, cooler and a more variable climate	Shift from stagnating bog growth to a phase of bog expansion found for ca. 3500 BC	+
Gunnarson et al. (2003)	Dendrochronological	Sweden	ca. 3600–3400 BC	Wet phase	Contemporary to cover of segment F (3602–3403 BC), including two dying-off pulses	+/–
Magny and Haas (2004)	Dendrochronological date, pollen and archaeological	Switzerland	ca. 3370 BC	Lake level rise	Last trees at TOMO_south died off 35 years previously	–

a long gap between site chronologies at TOMO_south).

The 8.2 ka event cooling phase, according to Thomas et al. (2007), began around ca. 6300 cal BC. Kobashi et al. (2007) date its beginning later, to ca. 6225 cal BC, while Veski et al. (2004) observe the time of maximum cooling for 6250–6150 varve years BC (Fig. 11b). Veski et al. (2004) also observe an abrupt end of the 8.2 ka cool period for 6080 varve years BC.

Dendrochronological data in proposed context with the event include a phase of pine establishment in Irish bogs from 6210 BC on (Torbenson et al., 2015), a phase of poor growth and regeneration of west German oaks from the river Main sediments at ca. 6270–6000 BC (Spurk et al., 2002) and a gap in the bog oak chronology at 6177–6060 BC (Achterberg et al., 2016). A pronounced glacier advance at Mont Miné in the Swiss Alps was dated to ca. 6175 BC using dendrochronology (Nicolussi and Schlüchter, 2012). The replication of the Eastern Alpine Conifer Chronology (Nicolussi et al., 2009) drops after 6250 BC for about 200 years. The replication of the Northwest German Pine Chronology (Achterberg et al., 2016) is also declining at the time, but does not reach particularly low levels.

The dates mentioned above correspond well in general. Particularly good agreement is found, for example, between the beginning of the gap in the Northwest German Bog Oak Chronology at 6177 BC (Achterberg et al., 2016) and the glacier advance dated by Nicolussi and Schlüchter (2012) to ca. 6175 BC, as well as between the end of said gap in the Northwest German Bog Oak Chronology at 6060 BC (Achterberg et al., 2016) and the end of the cool phase observed by Veski et al. (2004) for 6080 varve BC. The phases of unfavourable growth conditions observed at the river Main from ca. 6270 BC on (Spurk et al., 2002) and in the Alps from ca. 6250 BC on (Nicolussi et al., 2009) are in equally close agreement.

At site TOMO_south, a phase of frequent tree dying-off from 6250 to 6157 BC matches the time of maximum cooling (6250–6150 varve years BC) as described by Veski et al. (2004) and the beginning of the replication decline from ca. 6250 BC on in the Eastern Alpine Conifer Chronology (Nicolussi et al., 2009). The trees of TOMO_south display a strong dying-off pulse at ca. 6315 BC, which may relate to the event as Thomas et al. (2007) date it. However, the 8.2 ka event does not show as clearly in the pine record of TOMO_south as it does in other records.

Magny et al. (2004) describe several phases of high lake levels in central Europe, four of which are within the time frame covered at TOMO_south (In the following these are referred to as first to fourth phase, disregarding all which are outside of the time frame discussed here.) The first of these (ca. 6350–6100 cal BC) is also within the dying-off phase of segment A2 (6365–5733 BC). The beginning of the two phases (high lake levels in Magny et al., 2004, and dying-off at TOMO_south) are in close temporal accordance. The second phase of high lake levels, described by Magny et al.

(2004) for ca. 5600–5300 cal BC, does not fit the data of TOMO_south. The onset of the event is contemporaneous to a site chronology gap at TOMO_south, which is taken to indicate dry conditions rather than wet ones, and its end is contemporaneous to the beginning of a dying-off phase at TOMO_south (segment B, 5308 BC), which should indicate the beginning of a more humid period rather than its end.

The data of Schmidt et al. (2004) seem to be in contradiction to the record of TOMO_south at that time as well. They show data from 5600 BC on, which displays more or less humid conditions until about 5420 BC. This is within a chronology gap at TOMO_south, with the gap end (5404 BC) closely meeting the end of the relatively humid conditions observed in the data of Schmidt et al. (2004). The subsequent dry phase displayed by Schmidt et al. (2004) for ca. 5400–5350 BC fits the indications from TOMO_south better, where the pines begin establishment contemporary to the dry phase beginning and start dying off only after the dry phases end, in 5308 BC. The two wet phases that follow according to Schmidt et al. (2004) (ca. 5320–5000 and ca. 4950–4900 BC) fit the dying-off phase of segment B at TOMO_south (5308–4902 BC), which also indicates humid conditions. The beginning of the above dying-off phase is temporally close to the beginning of the first of the two mentioned wet phases, and the end of the dying-off phase is contemporary to the end of the second. This is a very close agreement of the indications of the two dendrochronological records. The interjacent dry phase (ca. 5000–4950 BC) documented by Schmidt et al. (2004) is not reflected in TOMO_south.

Gunnarson et al. (2003) describe drier conditions for ca. 4900–4800 BC. At TOMO_south a site chronology gap (4901–4838 BC) begins at the same time. The gap and the following phase of tree establishment conform to drier conditions.

More humid conditions are evident from pollen and peat data composed in the context of a trackway (Bauerochse, 2003), which is dendrochronologically dated (construction and maintenance 4629–4545 BC) (Bauerochse et al., 2012; Achterberg et al., 2015). The palaeo-botanical indications for increased humidity described by Baueroche (2003) can thus be aligned to the dying-off phase of site chronology segment C (4712–4537 BC).

The third phase of high lake levels described by Magny et al. (2004) (ca. 4400–3950 cal BC) does not coincide with indications for increased humidity at TOMO_south. It begins within a long site chronology gap (4536–3987 BC) and ends before the beginning of the next dying-off phase. There are, however, die-off phases of northwest German pines from other bogs which date to ca. 4490–4370, 4230–4170 and ca. 4010–3960 BC (Achterberg et al. 2015), contemporary to that phase of high lake levels described by Magny et al. (2004) for ca. 4400–3950 cal BC (Fig. 11a and b). Turney et al. (2006), on the other hand, state drier conditions for Ireland around ca. 4250 BC, also dating within the TOMO_south site chronology gap 4536–3987 BC, which is in agreement with our interpretation of the TOMO_south data.

Palynological indications for increased humidity (Bauerochse, 2003) are temporally anchored to after 3701 BC by a dendrochronologically dated trackway (Bauerochse et al., 2012; Achterberg et al., 2015). This is within the dying-off phase of segment E at TOMO_south (3691–3614 BC), and therefore in agreement with its climatic indication. Around the same time Arbogast et al. (2006) also identify climatic deterioration, a shift towards cooler and possibly more humid conditions for ca. 3700–3250 BC. Magny et al. (2004) date the beginning of their fourth phase of high lake levels to ca. 3700 cal BC as well (ca. 3700–3250 cal BC). Despite the low replication of segment E, these coherences make the indication of its dying-off phase appear quite valid.

The wet phase observed by Gunnarson et al. (2003) for ca. 3600–3400 BC covers about the same time as segment F. Tree die-off in segment F (indicating water table rise) starts later though, at ca. 3500 BC. However, both dying-off pulses of segment F are therefore within the wet phase documented for Sweden (Gunnarson et al., 2003), with the end of the wet phase meeting the end of the last dying-off pulse. This makes for an intermediate level of agreement.

Dreslerova (2012) points out a pronounced shift towards wetter, cooler and a more variable climate around ca. 3550 cal BC, reviewing numerous European studies of climate proxy for the Holocene. The TOMO_south dying-off phase 3496–3473 BC (segment F) may well relate to this event, which Dreslerova (2012) describes to be the beginning of a significant climatic phase.

The tree ring chronologies of TOMO_south do not cover the end of the Holocene Thermal Maximum, which occurred around ca. 2350 cal BC with a shift to cooler conditions (Seppä et al., 2005).

The trees of TOMO_south record water table change at one mire. The water table changes are largely driven by precipitation in the catchment area but are also affected by evapotranspiration. This hydrological signal has a higher temporal resolution due to its local nature than an supra-regional record (such as Achterberg et al., 2015) would. Even though the climatic drivers are the same in both cases, regional variations in rainfall, for example, are smoothed out in a supraregional record at the cost of precision, which would in turn be retained in a case study such as this.

Even though the dating of the trees and their reactions to environmental change is precise to the calendar year, that does not necessarily apply to the dating of the related climatic causes. The water table rise observed in mires can be lagged behind the climatic shifts by months or even years (Edvardsson et al., 2016).

5. Conclusions

The trees, stratigraphically located at the fen–bog transition, are viewed to stem from the former bog margin, being embedded by the expanding raised bogs Sphagnum peat. The tree dates document a raised bog expansion at the site for 6614–6436 (ca. 250 years), 6365–5733 (ca. 750 years), 5308–4902 (ca. 500 years), 4712–4537 (ca. 300 years), 3895–3838 (ca. 150 years), 3691–3614 (ca. 200 years), 3496–3473 (ca. 25 years) and ca. 3400 BC (4 years). These phases of lateral raised bog growth likely occurred in periods of rather humid climate.

The shorter gaps between the later site chronologies are viewed as insignificant, since they belong to poorly replicated periods documented at the site's margin. The three longer gaps between the earlier site chronology segments, however, are framed by well-replicated sections represented in the central area of the site. These are interpreted to represent periods without significant (and lasting) raised bog advance, since the site is throughout covered with stumps and these were densely sampled. These chronology gaps relating to phases of apparent bog stagnation are 5733–5308 (328 years), 4902–4712 (64 years) and 4537–3895 BC (550 years). There are, however, dying-off phases recorded at other northwest German bogs within these periods. These periods therefore do not appear to have been throughout dry phases in the region.

The distribution of the tree stumps of various ages across the site supports the picture of subsequent bog advance embedding the tree stumps. The bog expanded from the southeast towards north-west according to the dating of the trees, the direction of bog growth largely reflecting the elevation of the mineral base below the peat. Rises of the sandy ground formed wooded islands within the bog, being successively covered by Sphagnum peat with much delay.

6. Data availability

The corresponding datasets are available at pangaea.de (Achterberg et al., 2017):
https://doi.pangaea.de/10.1594/PANGAEA.884249,
https://doi.pangaea.de/10.1594/PANGAEA.884247,
https://doi.pangaea.de/10.1594/PANGAEA.884248,
https://doi.pangaea.de/10.1594/PANGAEA.884212.

7. Competing interests

The authors declare that they have no conflict of interest.

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9. References

Achterberg, I., Bauerochse, A., Giesecke, T., Metzler, A., and Leuschner, H.: Contemporaneousness of Trackway construction and environmental change: a dendrochronological study in Northwest-German mires, IANSA, 6, 19–29, 2015.

Achterberg, I., Frechen, M., Bauerochse, A., Eckstein, J., and Leuschner, H. H.: The Goettingen tree-ring chronologies of peatpreserved oaks and pines from northwest Germany, ZDGG – German Journal of Geosciences (German J. Geol.), 168, 9–19, 2017.

Achterberg, I. E. M., Eckstein, J., Birkholz, B., Bauerochse, A., Leuschner, H. H.: Dendrochronological dates of subfossil pines (Pinus sylvestris L.), relative dates of floating chronology, and peat stratigraphy from site “TOMO_south” at Totes Moor, northwest Germany, PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.884249, 2017.

Achterberg, I. E. M., Eckstein, J., Birkholz, B. et al.: Dendrochronological dates of subfossil pines (Pinus sylvestris L.) of site TOMO_south, https://doi.pangaea.de/10.1594/PANGAEA.884247, 2017.

Achterberg, I. E. M., Eckstein, J., Birkholz, B. et al.: Peat stratigraphy of site TOMO_south, https://doi.pangaea.de/10.1594/PANGAEA.884212, 2017.

Achterberg, I. E. M., Eckstein, J., Birkholz, B. et al.: Relative dates of floating chronology of subfossil pines (Pinus sylvestris L.) of site TOMO_south, https://doi.pangaea.de/10.1594/PANGAEA.884248, 2017.

Arbogast, R. M., Jacomet, S., and Magny, M.: The significance of climate fluctuations for lake level changes and shifts in subsistence economy during the Late Neolithic (4300–2400 BC) in Central Europe, Veg. Hist. Archaeobot., 15, 403–418, 2006.

Bauerochse, A.: Environmental change and its influence on trackway construction and settlement, in: Peatlands, archaeological sites – archives of nature, nature conservation, wise use, edited by: Bauerochse, A. and Hassmann, H., Proceedings of the Peatland Conference 2002 in Hannover, Germany, Rahden/Westfahlen, 66–76, 2003.

Bauerochse, A., Leuschner, H. H., and Metzler, A.: Das Campemoor im Neolithikum, Jahrbuch für das Oldenburger Münsterland 2012, 61. Jahrgang, Heimatbund für das Oldenburger Münsterland, 2012.

Behre, K.-E.: Landschaftsgeschichte Norddeutschlands – Umwelt und Siedlung von der Steinzeit bis zur Gegenwart, Wachholtz Verlag Neumünster, 308 pp., 2008.

Bronk Ramsey, C.: Baysian analysis of radiocarbon dates, Radiocarbon, 51, 337–360, 2009.

Bronk Ramsey, C., van der Plicht, J., and Weninger, B.: “Wiggle matching” radiocarbon dates, Radiocarbon, 43, 381–389, 2001.

Dreslerova, D.: Human Response to Potential Robust Climate Change in the Territory of Bohemia (the Czech Republic), Nat. Sci. Arc., 3, 43–55, 2012.

Eckstein, J., Leuschner, H. H., Bauerochse, A., and Sass-Klaassen, U.: Subfossil bog-pine horizons document climate and ecosystem changes during the Mid-Holocene, Dendrochronologia, 27, 129–146, 2009.

Eckstein, J., Leuschner, H. H., Giesecke, T., Schumilovskikh, L., and Bauerochse, A.: Dendroecological investigations at Venner Moor (northwest Germany) document climate-driven woodland dynamics and mire development in the period 2450–2050 BC, Holocene, 20, 231–244, 2010.

Eckstein, J., Leuschner, H. H., and Bauerochse, A.: Mid-Holocene pine woodland phases and mire development – significance of dendrochronological data from subfossil trees from nortwest Germany, J. Veg. Sci., 22, 781–794, 2011.

Edvardsson, J., Leuschner, H. H., Linderholm, H., and Hammarlund, D.: South Swedish bog pines as indicators of Mid-Holocene climate variability, Dendrochronologia, 30, 93–103, 2012a.

Edvardsson, J., Linderson, H., Rundgren, M., and Hammarlund, D.: Holocene peatland development and hydrological variability inferred from bog-pine dendrochronology and peat stratigraphy – a case study from southern Sweden, J. Quaternary Sci., 27, 553–563, 2012b.

Edvardsson, J., Poska, A., van der Putten, N., Rundgren, M., Linderson, H., and Hammarlund, D.: Late-Holocene expansion of a south Swedish peatland and its impact on marginal ecosystems: evidence from dendrochronology, peat stratigraphy and paleobotanical data, Holocene, 24, 466–476, 2014.

Edvardsson, J., Stoffel, M., Corona, C., Bragazza, L., Leuschner, H.H., Charman, D. J., and Helama, S.: Subfossil peatland trees as proxies for Holocene palaeohydrology and palaeoclimate, Earth-Sci. Rev., 163, 118–140, 2016.

Ellenberg, H.: Vegetation Mitteleuropas mit den Alpen, Ulmer Stuttgart, 1096 pp., 1996.

Gunnarson, B., Bogmark, A., andWastergård, S.: Holocene humidity fluctuations in Sweden inferred from dendrochronology and peat stratigraphy, Boreas, 32, 347–360, 2003.

Holmgren, M., Lin, C.-Y., Murillo, J., Nieuwenhuis, A., Penninkhof, J., Sanders, N., van Bart, T., van Veen, H., Vasander, H., Vollebregt, M., and Limpens, J.: Positive shrub-tree interactions facilitate woody encroachment in boreal peatlands, J. Ecol., 103, 58–66, https://doi.org/10.1111/1365-2745.12331, 2015.

Hughes, P. and Barber, K.: Contrasting pathway to ombrotrophy in three raised bogs in Ireland and Cumbria, England, Holocene, 14, 65–77, 2004.

Kobashi, T., Severinghaus, J. P., Brook, E. J., Barnola, J.-M., and Grachev, A. M.: Precise timing and characterization of abrupt climate change 8200 years ago from air trapped in polar ice, Quaternary Sci. Rev., 26, 1212–1222, 2007.

Krąpiec, M., Margielewski,W., Korzenn´, K., Szychowska-Krąpiec, E., and Łajczak, A.: Late Holocene palaeoclimate variability: The significance of bog pine dendrochronology related to peat stratigraphy, The Pu´scizna Wielka raised bog case study (Orawa – Nowy Targ Basin, Polish Inner Carpathians), Quaternary Sci. Rev., 148, 192–208, 2016.

Leuschner, H. H., Sass-Klaassen, U., Jansma, E., Baillie, M. G. L., and Spurk, M.: Subfossil European bog oaks: population dynamics and long-term growth depressions as indicators of changes in the Holocene hydro-regime and climate, Holocene, 12, 695–706, 2002.

Leuschner, H. H., Bauerochse, A., and Metzler, A.: Environmental change, bog history and human impact around 2900 B.C. in NW Germany – preliminary results from a dendroecological study of a sub-fossil pine woodland at Campemoor, Dümmer Basin, Veg. Hist. Arc., 16, 183–195, 2007.

Limpens, J., Holmgren, M., Jacobs, C., Van de Zee, S., Karofeld, E., and Berendse, F.: How does tree density affect water loss of peatlands? A mesocosm Experiment, PLOS One, 9, 1–11, 2014.

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

Meier-Uhlherr, R., Schulz, C., and Luthardt, V.: Steckbriefe Moorsubstrate, 2. unveränd. Aufl., HNE Eberswalde, Berlin, 2015.

Metzler, A.: Moorarchäologie in Niedersachsen, in: Archäologie, Land, Niedersachsen: 25 Jahre Denkmalschutzgesetz – 400.000 Jahre Geschichte, edited by: Fansa, M. and Both, F., Archäologische Mitteilungen aus Nordwestdeutschland, Beiheft 43, Landesmuseum Natur und Mensch Oldenburg, 471–475, 2004.

Moir, A. K., Leroy, S., Brown, D., and Collins, P.: Dendrochronological evidence for a lower water-table on peatland around 3200–3000 BC from subfossil pine in northern Scotland, Holocene, 20, 931–942, 2010.

Nicolussi, K. and Schlüchter, C.: The 8.2 ka event – Calendardated glacier response in the Alps, Geology, 40, 819–822, https://doi.org/10.1130/G32406.1, 2012.

Nicolussi, K., Kaufmann, M., Melvin, T. M., van der Plicht, J., Schießling, P., and Thurner, A.: A 9111 year long conifer treering chronology for the European Alps: a base for environmental and climatic investigations, Holocene, 19, 909–920, 2009.

Overbeck, F.: Das Große Moor bei Gifhorn – im Wechsel hygrokliner und xerokliner Phasen der nordwestdeutschen Hochmoorentwicklung, Niedersächsisches Amt für Landesplanung und Statistik, Veröffentlichungen Reihe A I, Band 41,Walter Dorn Verlag, Bremen-Horn, 1952.

Overbeck, F.: Botanisch-geologische Moorkunde – unter besonderer Berücksichtigung der Moore Nordwestdeutschlands als Quellen zur Vegetations-, Klima- und Siedlungsgeschichte, Karl Wachtelholz Verlag Neumünster, 1975.

Petzelberger, B., Behre, K.-E., and Geyh, M.: Beginning and spread of raised bogs Northwest Germany – first results of a new project, Telma, 29, 21–38, 1999.

Reimer, P., Baillie, M., Bard, E., Bayliss, A., Beck, J., Blackwell, P., Bronk Ramsey, C., Grootes, P., Guilderson, T., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T., Hoffmann, D., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., Manning, S., Niu, M., Reimer, R., Richards, D., Scott, E., Southon, J., Staff, R., Turney, C., and van der Plicht, J.: IntCal13 and Marine 13 radiocarbon age calibration curves, 0–50,000 years cal BP, Radiocarbon, 55, 1869–1887, 2013.

Riemer T.: Über die Varianz von Jahrringbreiten – Statistische Methoden für die Auswertung der jährlichen Dickenzuwächse von Bäumen unter sich ändernden Lebensbedingungen, Berichte des ForschungszentrumsWaldökosysteme, Reihe A, 121, 1–375, 1994.

Rinn, F.: TSAP-Win: Time Series Analysis and Presentation for Dendrochronology and related Applications, Version 0.55 User reference, Heidelberg, Germany, 2003.

Schmidt, B., Gruhle, W., and Rück, O.: Klimaextreme in Bandkeramischer Zeit (5300 bis 5000 v. Chr.), Interpretation dendrochronologischer und archäologischer Befunde, Archäologisches Korrespondenzblatt, 34, 303–308, 2004.

Schweingruber, F.: Tree Rings – Basics and Application of Dendrochronology, 276 S. D. Reidel Publishing Company, Dordrecht, Holland, 1988.

Seppä, H., Hammarlund, D., and Antonsson, K.: Low-frequency changes in temperature and effective humidity during the Holocene in south-central Sweden: implications for atmospheric and oceanic forcings of climate, Clim. Dynam., 25, 285–297, https://doi.org/10.1007/s00382-005-0024-5, 2005.

Shumilovskikh, L., Schlütz, F., Achterberg, I., Kvitkina, A., Bauerochse, A., and Leuschner, H. H.: Pollen as a nutrient source in Holocene ombrotrophic bogs, Rev. Palaeobot. Palyno., 221, 171–178, 2015.

Spurk, M., Leuschner, H., Baillie, M., Briffa, K., and Friedrich, M.: Depositional frequency of German subfossil oaks: climatically induced fluctuations in the Holocene, Holocene 12, 707–715, 2002.

Stenzel, V.: Dendroökologische Untersuchungen zum räumlichzeitlichen Wachstum eines subfossilen Kiefernwaldes im Toten Moor (bei Neustadt am Rübenberge in Niedersachsen), Bachelorarbeit, Abteilung Palynology und Klimadynamik, Albrecht-von-Haller-Institut für Pflanzenwissenschaften, Biologische Fakultät, Universität Göttingen, 2013.

Tahvanainen, T.: Abrupt ombrotrophication of a boreal aapa mire triggered by hydrological disturbance in the catchment, J. Ecol., 99, 404–415, 2011.

Thomas, E., Wolff, E., Mulvaney, R., Steffensen, J., Johnsen, S., Arrowsmith, C., White, J., Vaughn, B., and Popp, T.: The 8.2 ka event from Greenland ice cores, Quaternary Sci. Rev., 26, 70–81, 2007.

Torbenson, M., Plunkett, G.,Brown, D., Pilcher, J., and Leuschner, H. H.: Asynchrony in key Holocene chronologies: Evidence from Irish bog pines, Geology, 43, 799–802, 2015.

Turney, C., Baillie, M., and Palmer, J.: Holocene climatic change and past Irish societal response, J. Archaeol. Sci., 33, 34–38, 2006.

Veski, S., Seppä, H., and Ojala, A.: Cold event at 8200 yr B.P. recorded in annually laminated lake sediments in eastern Europe, Geology, 32, 681–684, 2004.

von Bülow, K.: Die Bedeutung der Versumpfung für die Entstehung von Hochmooren in Deutschland, Geol. Rund., 26, 277–284, 1935.

Zackrisson, O., Nilsson, M.-C., Steijlen, I., and Hörnberg, G.: Regenration pulses and climate-vegetation interactions in nonpyrogenic boral Scots pine stands, J. Ecol., 83, 469–483, 1995.