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, but 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. We investigated 13 peat-preserved trackways from the Northwest-German lowland 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 clearly notable die-off phases of trees preserved in the mires. As an 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. Overall, the majority of trackway constructions were found to be contemporaneous to mire water table rise and mire expansion. Possibly, a period of water table rise was a motivation for trackway construction.

1. Introduction

The northwest-German lowland changed in the millennia following the last glacial: from a periglacial wasteland to a forest-wetland mosaic, a landscape 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 southwest 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 the mostly short (decadal) phases of water table rise in northwest Germany. Indications for increased humidity in trackway layers have been 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 due to the large dendrochronological record of peat-preserved trees, originating from former mire (and mire-margin) woodland

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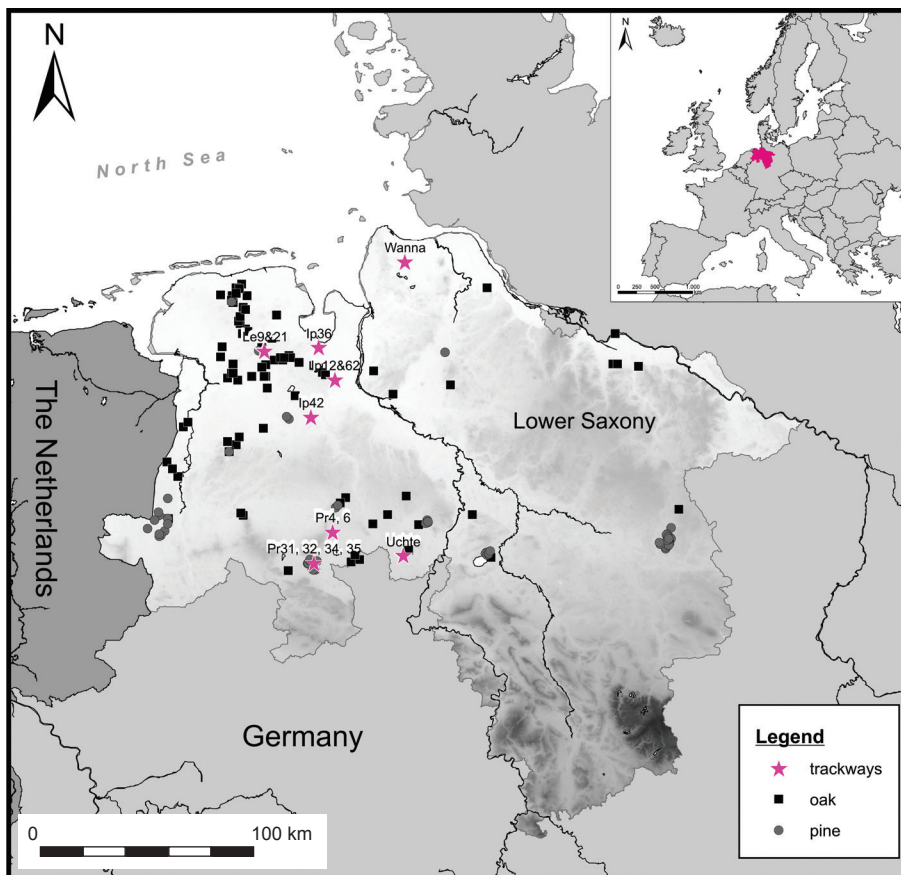
Figure 1. Study area in northwest Germany. Elevations are shaded and sampling sites indicated.

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, for example, 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 2010). 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 an 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 on the basis 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.

2. Material and methods

2.1 The peat-preserved trees of northwest Germany

The tree species regarded in this study only include oak (*Quercus* spec.) and pine (*Pinus sylvestris*). 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 remains are only tree stumps and stems; 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 the 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 northwest 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.

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Generally, tree die-off reflects (a period of) 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 fluctuations (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 indicating the beginning of 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 these 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

Table 1. The dendrochronologically-dated trackways of the northwest-German lowland. Dates refer to the last measured ring.

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 BC1	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

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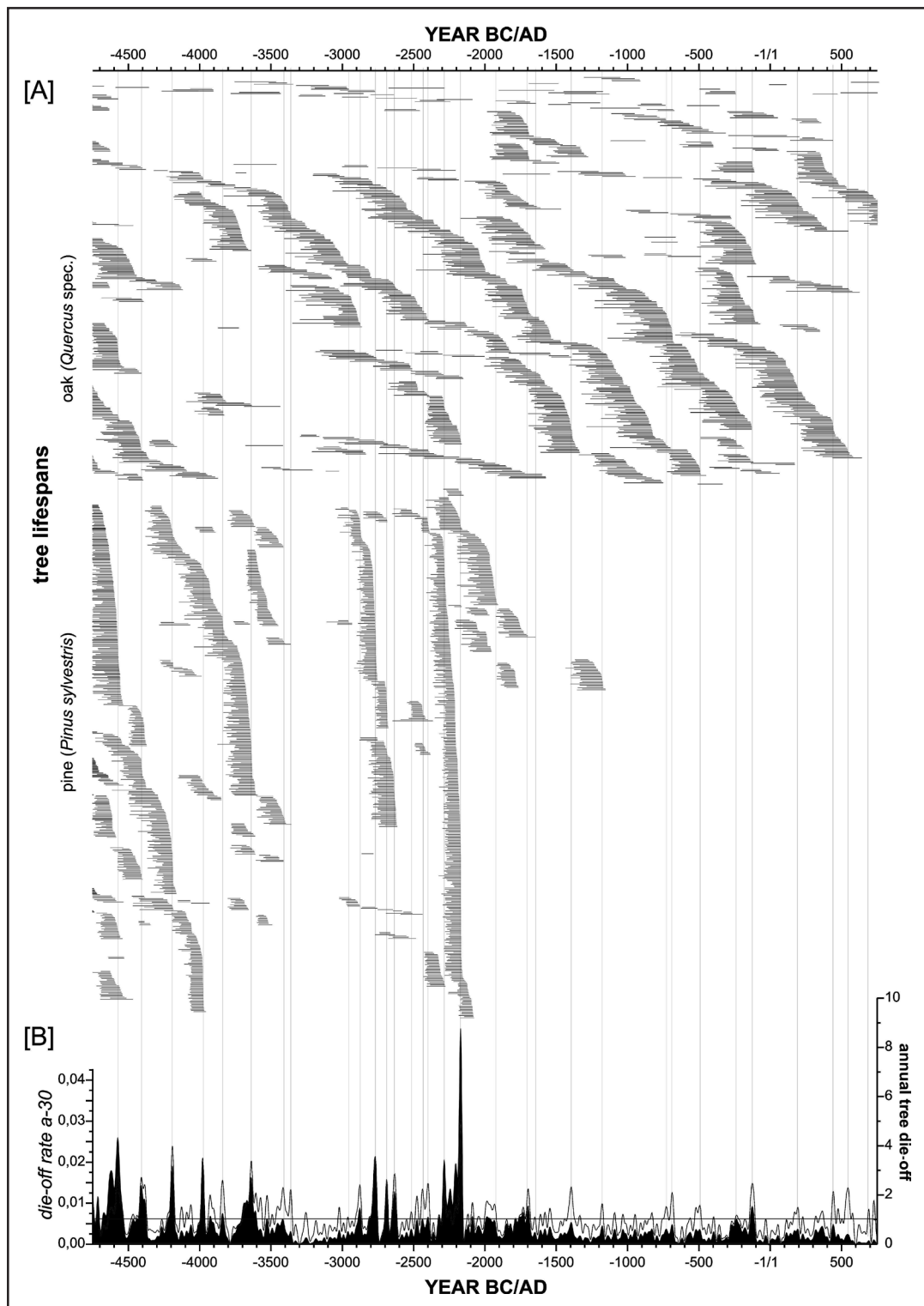
Figure 2. [A] gives the lifespans of trees, sorted by time of death and mire area of origin (several sites taken together). Severe die-off events are indicated by vertical lines (grey). [B] gives the annual tree die-off (black filled, scale on the left), and the corresponding *die-off rate a-30* (black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

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.

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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*). Conversely, one trackway appeared under 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).

2.2.1 Excluded trackways

Five dendrochronologically-dated trackways were excluded, because erosion and decay on the outer parts of 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 section 1, the peat-preserved trees from the area display synchronous phases of tree-establishment and common die-off. The die-off phases in particular 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, a measure called **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 closely examined 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.
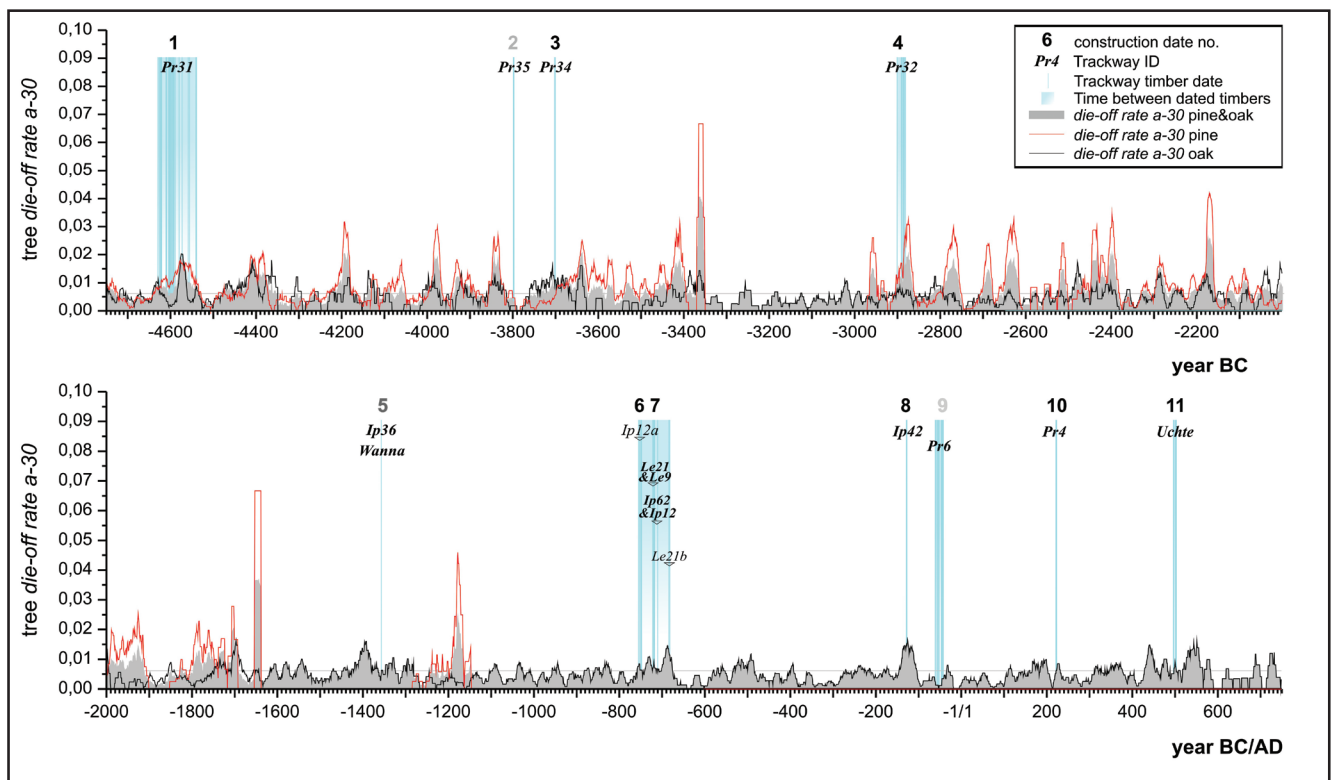
Figure 3. The *die-off rate a-30* is displayed for oaks (black), pines (red), smoothed by a 15-year running mean. The *tree die-off rate a-30* (average of the other two curves) is shown (grey, filled) with its mean value (grey horizontal line). The trackway timber dates are indicated by vertical lines (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.

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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 it was still possible to count them.

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 (section 3.2, Figure 3), which indicated water table rise and mire expansion (see sections 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 some decades (Figures 2 and 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 Figures 2a and 3a, compare section 2.1.).

In the study period examined, from 4750 BC to 750 AD, the distribution and appearance of die-off phases varied 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 stretched out, as the trees die successively along an elevation gradient. An example of the discrepancy between the species is the pine-only die-off peak around 2740 BC.

After c. 1500 BC, there are only a 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.

3.2 Contemporaneity of trackway construction and die-off phases of the peat-preserved trees
Nine of the eleven trackway construction dates (81%) clearly date 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 the context of environmental change nonetheless. By contrast, 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
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; Figure 4) 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 Figures 3a and 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 the 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 stretched-out long with three peaks (Figure 2a). It is reflected similarly by both tree species, with some minor differences (Figure 4c).
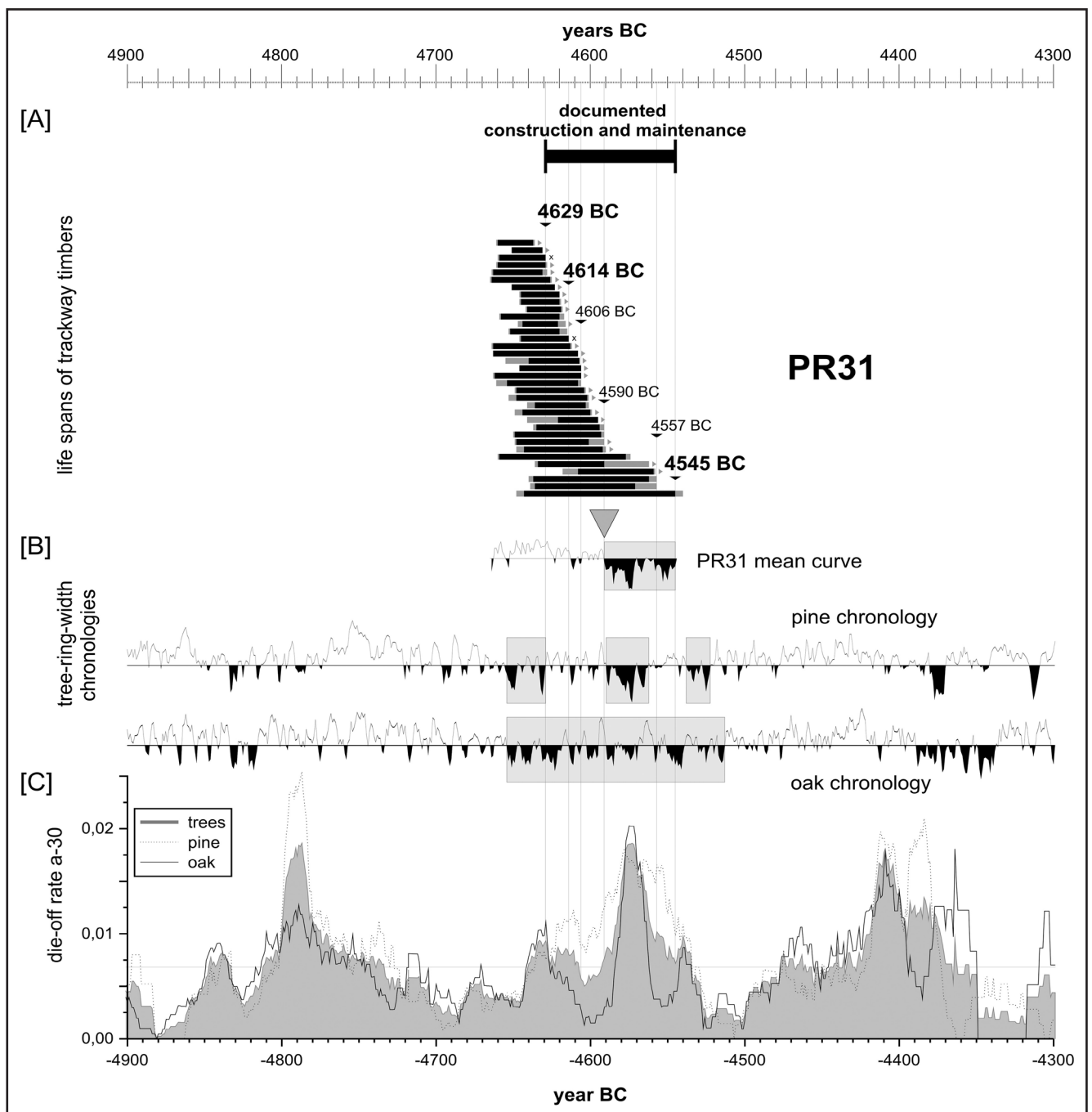
Figure 4. [A] shows the life spans of the trackway timbers from *Pr31*. Measured rings in black, missing rings are indicated in grey. Grey arrows indicate where more rings may be missing. Timbers with sure bark edge are indicated with ‚x'. Clustering dates, sure felling dates and the last acquired date 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 are scattered 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 have come to a halt, as only two, not fully preserved, timbers date within the following 30 years. This apparent

halt in maintenance is contemporaneous to the main peaks of the die-off phase (Figure 4c, and also Figure 2a), as well as two 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, the halt in maintenance, 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 discussion

This comparison shows a considerable temporal agreement of trackway construction with tree die-off phases: nine of the eleven trackway construction dates, corresponding to ten of the 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 within the context of 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 a subject for discussion is the reason for the observed correlation. There are two possible explanations: firstly, the correlation might be due to the 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 data presented here indicate that the opposite is the case, showing that the constructions follow a water table rise. This does not point towards a conservation bias, but rather towards an environmental change influencing construction activity.

Conservation conditions in the mires were generally good over long periods. This is indicated by the thick continuous layers of weakly decomposed peat and well-preserved ancient wood, found just below the mire surface. This is particularly true for 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 have been described (Metzler 2006), however, 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, the impact of varying conservation conditions cannot be ruled out entirely, at least 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 at a landscape-level surely affected the human population: in their land use, mobility, economics and social stability. Environmental changes and socio-cultural dynamics are interwoven 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 has repeatedly been suggested for excavated trackways, mostly based on peat-stratigraphical and palynological indications (*i.e.* Bauerochse 2003; Behre 2005; Baillie and Brown 1996; Leuschner *et al.* 2002; 2007; Metzler 2003). Several authors see the motivation for the construction of trackways as being just such an environmental change (*e.g.* Bauerochse 2003; Behre 2005; Leuschner *et al.* 2007; Metzler 2003).

For the British Isles trackway constructions, clusters have been 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 construction activity and its contemporaneousness with short-term environmental changes. We agree, however, with Plunkett *et al.* (2013) that motivation for trackway construction in general is surely not monocausal.

The trackways were constructed very differently, some are narrow bridges, whereas others are firm wooden roads fit for wheeled traffic. Mire development should have affected all of them (Raftery 1996), for example, by the drowning of older trackways, impassability of previously walkable mires, or the 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

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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 (the wet fen at a raised bog margin) towards raised bogs in the British Isles (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 to the first steep rise of the tree die-off curve, and the last timber date to the final peak of the die-off phase. Within the period of over 80 years in which the trackway had been maintained, there is a 30 year activity gap, which agrees temporally 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 of the trackway, appear to be related to a 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 this site, which had already 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 southwest-England 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 (Brinnung 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-reaching 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 southwest England is located between Ireland and northwest Germany, a similar development there at the same 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 contemporaneity. It was found to have been constructed, as well as abandoned, in the context of a mire water table rise, uniquely recorded by on-site trees (Leuschner 2007).

In the 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 rate of replenishment, which can indicate moist periods. The site being at a low-elevation site near the coast, which had long been forested, the last trees died off shortly before. A site just further inland records a contemporaneous fen-bog-transition at the start of the die-off phase. Both sites point towards wetness. Most remarkable is the contemporaneous construction of two trackways in the same year, some 70 km apart from one 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 the vast majority (25 of 28 dated coffins) had been made within only fifty years, between 1391 and 1344 BC (Christensen *et 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 *et 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.

A 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 has been observed at other sites in Europe. Most prominently, the abandonment of the dwelling at Biskupin (Poland) has been connected to a 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 both a germination and 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 wet event (van Geel *et 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). In particular, 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 during 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 asl) of the northwest-German lowland (Schwartz 1990) and the adjacent northeast Netherlands (*e.g.* Waterbolk 1962) dates to 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 are broad constructions of massive oak split-planks, which appear fit for wheeled traffic and hence might have been part of a long-distance route 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 rises 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, besides the sociocultural aspects, the timing of trackway construction might commonly have been related to mire expansion and mire water table rises.

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