Sweet Track
site SWB
Project 7500

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Preserving and monitoring the Sweet Track (site SWB) Project 7500

Contents

1. SUMMARY

The early Neolithic Sweet Track is known to run for just under 2 km between the Polden Hills and the 'island' of Westhay in the central Brue valley. Near its southern end its route crosses a ridge of hard geology known as Shapwick Burtle. Previous monitoring work (Jones 2013) had suggested that the trackway was under threat of damage by desiccation in the areas beside the burtle. To counter this threat, a method of 'wrapping' the monument in a plastic membrane was undertaken based on a Dutch technique.

To install the membrane, it was necessary to excavate four trenches across the line of the Sweet Track in September 2016. These have provided evidence of the changing character of the structure as it approached the dry ground of Shapwick Burtle, augmenting the previous work in that area and at the nearby southern terminal of the trackway at the foot of the Polden hills.

Evidence of human activity was found in the peat above the trackway, in the form of cut roundwood and poles lying in the same orientation as the Sweet Track. Radiocarbon dating has shown that this activity was happening more than half a millennium after the Sweet Track had been built. This could either be coincidence or an indication that the line of the Sweet Track beside Shapwick Burtle was still memorialised long after it went out of use.

Monitoring of the burial environment over three years (end of March 2017 to November 2019) showed that there was no significant threat to the monument from desiccation during that period. The membrane had little observable beneficial effect over that time, except possibly to retain moisture longer over the spring/early summer. It is suspected that any potential benefit would only be apparent during a much drier summer when the water table is lower.

2. BACKGROUND

The Sweet Track (SM 27978) is a very early Neolithic wooden trackway, built as a single plank raised walkway across almost 2 km of reedswamp between the Polden hills to the south and the island of Westhay to the north (Figure 1). A wide range of Neolithic material culture was deposited beside the trackway, including polished stone and flint axes, flint arrowheads, fine pottery and a range of organic objects including a wooden bowl, a toy axe, yew pins, a possible bow, a stirrer, and a digging stick (Coles and Orme 1979; Coles et al 1973; Coles and Orme 1984; Coles and Brunning 2009). The unhafted condition of the axes and the presence of high-quality axes and pottery suggest that deliberate votive deposition was taking place, possibly the earliest example of such deposition from an anthropogenic structure in the UK. The trackway has been dated by dendrochronological analysis of the oak and ash planks used in its construction. This proved that wood was felled for its construction in the winter of 3807/6BC or early spring 3806, with repairs taking place to at least 3800 BC (Hillam et al 1990). A lifespan of 9–12 years has been proposed for the structure (Coles and Brunning 2009).

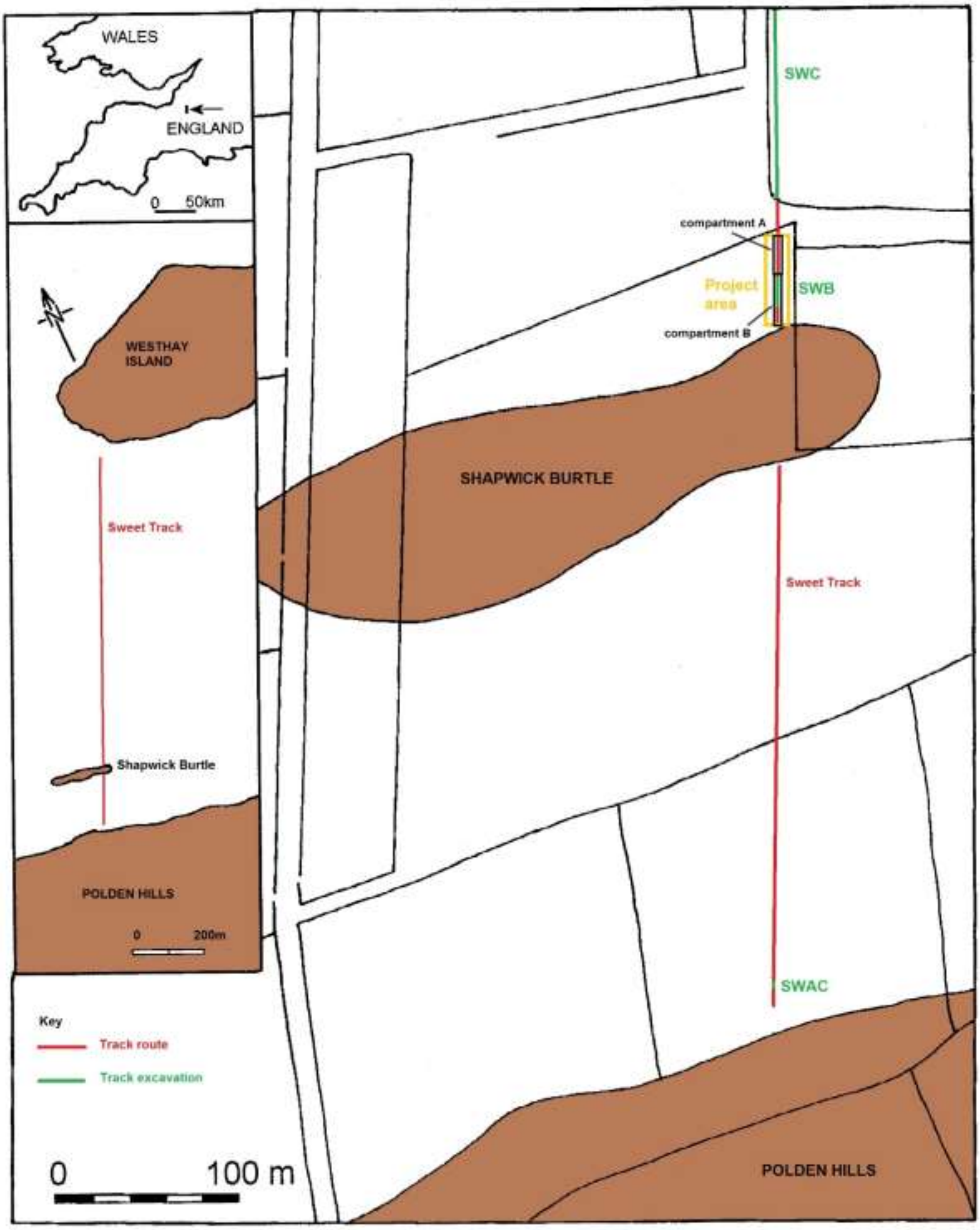

Figure 1. Sweet Track location. Excavated areas were named alphabetically from south to north (ie. SWB, SWC, SWD etc) by the Somerset Levels Project

The trackway was excavated by the Somerset Levels Project in two large areas, in advance of its destruction by peat extraction, one of which was area SWC (Figure 1). The probable southern end of the trackway was recorded at SWAC (Wells *et al* 1999) and another stretch of the trackway was excavated just north of Shapwick Burtle at site SWB (Coles *et al* 1973). Of the c.1.8 km length of the trackway, about 370 m has been excavated, and 550 m is preserved in situ in Shapwick Heath National Nature Reserve (Coles and Orme 1984, Coles and Coles 1986).

In the northern part of the reserve the trackway is protected by a pumping system maintained by Natural England. This feeds water into a ditch that runs beside the trackway, through an area of predominantly birch woodland. At the southern end of this system the pump feeds a ditch at the edge of a meadow field, from where water is taken either side of the trackway via underground irrigation pipes (Coles 1995). Monitoring of this system suggests that it is adequate to protect the trackway in these areas (Brunning et al 2000).

In the southern part of the reserve, two fields either side of the Shapwick Moor Rhyne contain the trackway in situ but do not benefit from the pumping system. In the northernmost of this pair of fields, a sand island, Shapwick Burtle, runs east-west across the line of the trackway (Figure 1). Detailed monitoring has previously been undertaken on the stretch of the Sweet Track (SWB) where it runs north from the sand island to the edge of the field (Jones 2013). Other excavations at the northern edge of Shapwick Burtle took place as part of the Mesolithic wetland/dryland edge project (Bell *et a*l 2015).

Previous excavation at the SWB site

A 12 m length of the trackway was uncovered in four separate trenches between 1971 and 1972 at the SWB site (Coles *et al* 1973). In this area the structure was significantly different from the raised plank walkway that had been created to cross the reedswamp further to the north. In the alder fen surrounding Shapwick Burtle island, the trackway route was defined by sparse horizontal timbers, patches of clay and charcoal, irregular groupings of upright posts and occasional bog oak trunks (Figure 2).

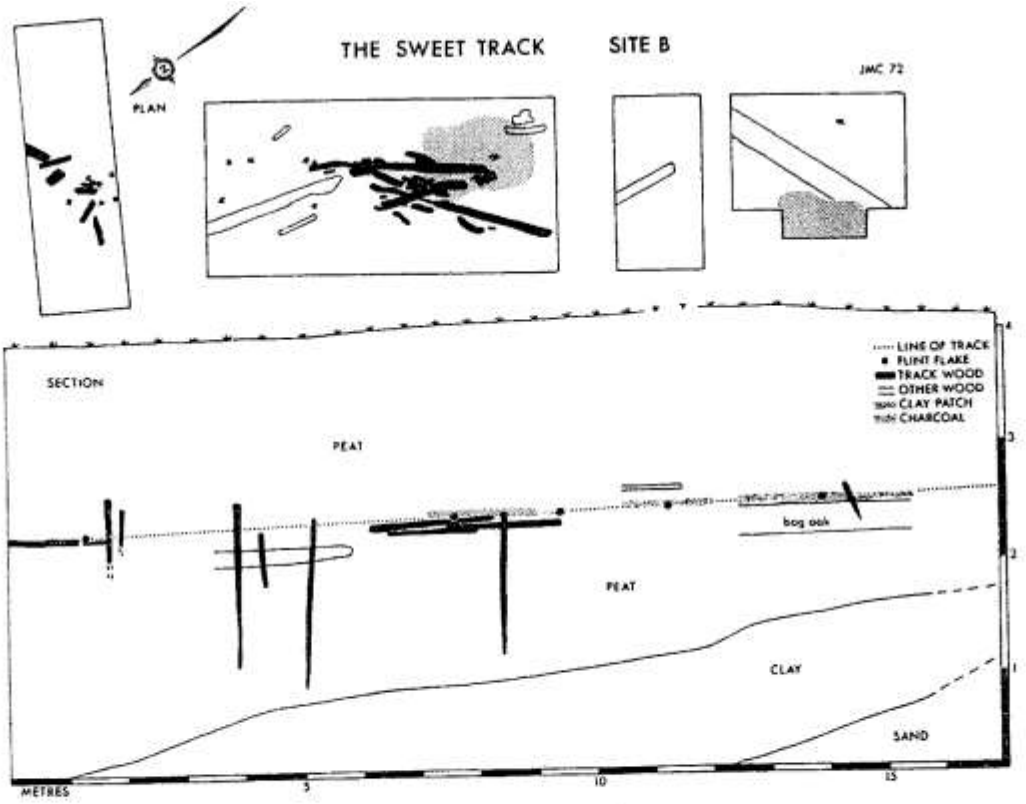

Figure 2. Plan and section of SLP excavations at SWB site

Over most of its length the trackway is between 1.50 m OD and 1.65 m OD. When it draws near to the Burtle it begins to rise up slightly (Coles *et al* 1973). The published cross section (Coles *et al* 1973, fig 11) shows the trackway timbers at c.1.5–1.7 m below the ground surface. Peat extends from the surface to estuarine clay that laps up against the sand deposit of the Shapwick Burtle island. The top of the clay is shown at 2.5–4 m below ground (Figure 2)

Subsequent coring has recorded the ground surface of the peat soils at the northern side of the sand island shelving down northwards from c.4–3.2 m OD (Jones 2103, fig.5.28). A well humified peat extends from the ground surface to c.1 m OD. Beneath this is a c.2 m deep layer of sandy silt which runs back to the edge of the island. Underneath that is a (late Mesolithic) peat (Wilkinson 1999, Bell *et al* 2015).

Previous monitoring at the SWB site

Previous monitoring at the SWB site was based on a transect established parallel to, but 5m east of, the trackway line. Fifteen sediment cores were taken along the transect, to describe the sedimentary sequence, examine humification and take samples for soil moisture, loss on ignition and particle size analysis (Jones 2013). Water levels and pH were monitored at eleven of the locations through piezometers at three different depths. Chemical analysis of groundwater samples was also undertaken for a period of 14 months. Redox was recorded once a month at five locations, at three depths at each site. Taken together this provides a very comprehensive set of baseline measurements against which to measure future change.

In the area north of the Burtle the water table fell below the presumed level of the trackway (at 2.5 m OD) between three and ten months of the year (Jones 2013, 165). The ditch at the northern edge of the field was often over 1 m below the groundwater level in the field and sometimes dried up completely in late summer. The water pH results varied from pH 4.4–7.9. The water chemistry data did not suggest any significant concern about water quality on the site (*ibid* 177-8).

Monitoring of the Sweet Track in meadow and wooded fields further north in the reserve showed similar peat soils were present (Brunning *et al*. 2000). The water table in those areas was, however, kept artificially above the track level all year round using a pumping system which topped up the ditch beside the track during the summer.

Dutch ‘Wrap a wreck’ method and results

Numerous post-medieval shipwrecks are known to exist in reclaimed parts of the Zuiderzee, in sand and/or clay deposits. Since the late 1970’s a method has been developed to mitigate the degradation process by wrapping them in plastic sheet. The methodology is almost the same as the detailed in the methods section below, except that in the Netherlands it was often necessary to build up a small mound over the site to help preserve the archaeology and the plastic from plough damage. A total of 17 wrecks were wrapped by this method up to 1992. The technique has recently been slightly updated using different installation material and a new type of plastic sheeting (Speleers *et al* 2016). The Dutch methodology is almost the same as the that detailed in the methods section below, except that in the Netherlands it was often necessary to build up a small mound over the site to help preserve the archaeology and the plastic from plough damage.

The monitoring of shipwrecks preserved by this method has shown that it has proved successful in preserving wooden remains and arresting fungal decay (Speleers *et al* 2016). One ship was wrapped in 1981, and its excavation in 1990 showed that no deterioration had taken place since the wrapping was installed (*ibid*). A 2008 study showed similar success with a wreck in Almere Port (Waldus 2008) and four wreck sites were studied as part of the BACPOLES project, one of which was a wrapped wreck. That site was shown to have wet, reducing conditions (Klassen 2005, 87) during a dry summer when the nearby ditches had run dry (Huisman *et al.* 2008). The plastic appears to prevent evapotranspiration and lateral sub surface flow, while at the same time channelling rainfall towards the centre of the site.

Research Aims

Aims

1. Enhance the burial environment of this section of the Sweet Track so that it can be taken off the Heritage At Risk Register
2. Enhance the existing data on the present condition of the site and the extent of survival of *in situ* remains
3. Determine which of the two wrapping methods is most successful in enhancing the burial environment
4. Determine if the project methodology can be successfully applied to other wetland monuments at risk in peat soils
5. Determine the key monitoring parameters that should be applied to similar schemes in the future

3. MEMBRANE INSTALLATION METHODOLOGY

The application of the Dutch wrapping methodology was modified, as detailed below, to fit the site conditions and to meet the aims and objectives of the project. The area of the Sweet Track to be protected was divided into two compartments (A and B) north of Shapwick Burtle. Each compartment was intended to be up to 30m long and 8m wide (Figure 3). A 400mm wide trench was excavated around the perimeter of each compartment to permit the installation of the plastic membrane.

In three locations the perimeter trench had to cross the line of the Sweet Track, on the northern and southern edges and in the division between the compartments (Figure 3). In these areas archaeological excavation took place. This was done to mitigate the impact on the monument, to permit condition samples to be taken from the structure and to confirm the depth of the monument as it approached the island of Shapwick Burtle to the south. Each trench was up to 2 m wide and was to be excavated to the depth of the trackway. As the southern trench (3) encountered only a thin covering of desiccated peat over the sand of the island, an additional trench (4) was excavated a few metres to the north to find a more suitable location for the compartment edge. The internal lengths of the compartments were therefore reduced to 27 m for A and 20 m for B.

In each trench any worked wood was numbered individually, planned, levelled and lifted for further analysis. Oak timbers were visually identified (by Brunning) and other species were identified microscopically by Dana Challinor.

Within the compartments the top 0.5m of desiccated peat was removed by machine under archaeological supervision and piled to one side. The exposed surface was graded to gently slope towards the centre line of each compartment (ie. above the line of the trackway). An impermeable 0.5mm thick plastic membrane (polyolefin-based homogenous polypropylene Aquatex EX®) was manually positioned in the perimeter trenches and spread horizontally across the graded surface leaving a 500mm wide central gap running along the line of the trackway (photos Appendix D). This was to allow rainfall to be channelled down the upper surface of this sloping plastic sheet towards the gap. Each compartment was covered by two sheets, one either side of the central gap. The sheet was then re-covered by the excavated peat and allowed to naturally reseed (at the request of Natural England).

In the northern compartment (A) the membrane was inserted to a depth of 1m below the top of the trackway in the boundary trench, with its base resting in peat, while the southern compartment (B) had a boundary trench cut deeper, to c.3-3.5m below ground, allowing the membrane to key into the underlying clay deposits. Where the excavation was carried into the clay deposits the membrane had to be inserted rapidly because the sides of the trench rapidly became unstable. This meant that it was only possible to excavate into the top c.200mm of the clay because any greater depth would cause collapse.

The methodologies for wood condition assessment and monitoring of the burial environment are detailed in the relevant appendices (A-C).

4. FIELDWORK RESULTS

A total of four trenches were excavated (Figure 3) and were given the Somerset museum accession number TTNCM 100/2016. The most northerly (Trench 1) was where the trackway was thought to be most deeply buried and therefore best preserved. Trench 2 was located at the junction between compartments A and B, in the area of the previous excavations by the Somerset Levels Project (Coles *et al.* 1973). Trench 3 was opened towards the northern edge of Shapwick Burtle island. As the peat deposits in that location were extremely thin, a fourth trench was excavated further north to encompass the southern boundary of compartment B.

Wood species identifications were undertaken by Dana Challinor, except for visual identification of oak done by Richard Brunning. The species of each piece of wood are listed in appendix 3.

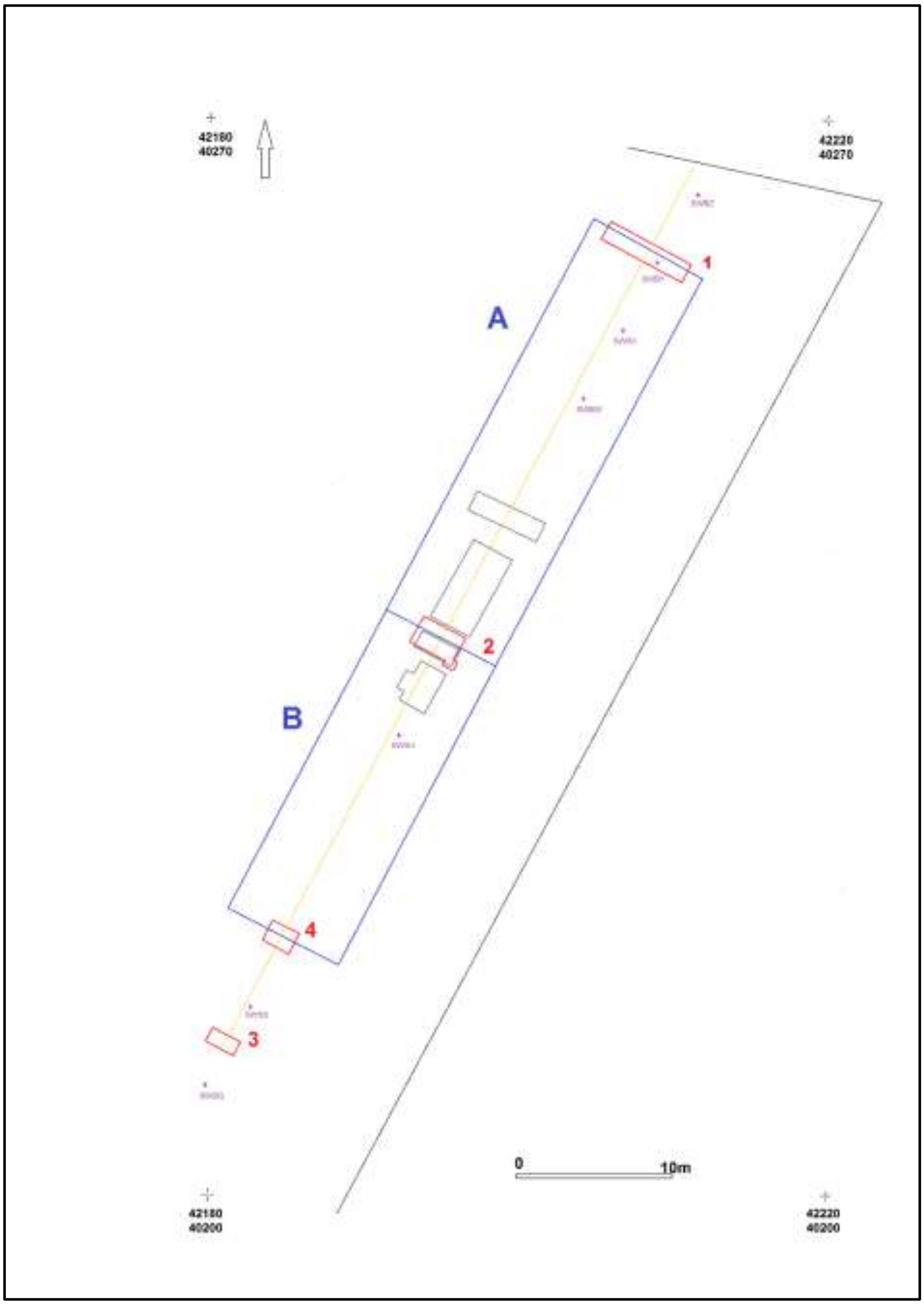

Figure 3. Location plan of trenches (red), SLP trenches (light blue), previous monitoring stations, and membrane compartments A and B.

Trench 1

This trench was positioned on the northern edge of compartment A. As it was the trench furthest from Shapwick Burtle island, it was expected that the trackway would be at its lowest depth in this location. The trench was 6.5 m long and 1.5 m wide.

Sweet Track

The lowest pieces of worked wood consisted of a series of small woodchips (59, 60, 61, 62, 64a, 65, 67, 68, 70, 71), bark (63), roundwood (66), split pieces (64b, 69, 73) and the tip of a small stake (74) (Fig. 4.C). Immediately above these, the Sweet Track structure was encountered at a depth of 1.8-1.5 m below ground (1.68-1.85 m OD). The lowest structural components were a series of holly and ash small logs (17, 34) and radially split ash planks or offcuts (26, 27, 72) running roughly NNE-SSW along the known line of the trackway route.

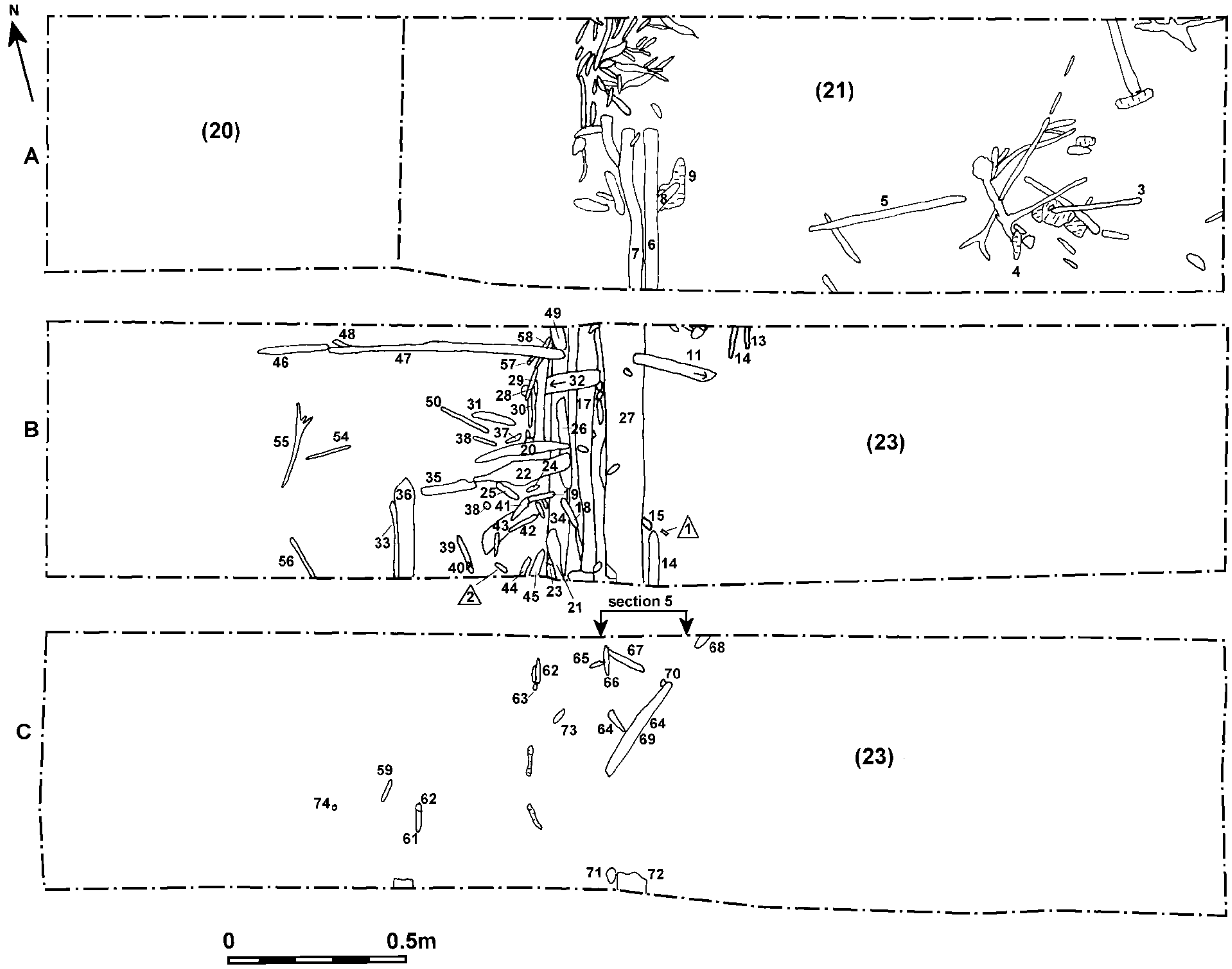

Figure 4. Trench 1. A – upper wood; B – Sweet Track; C – lower Sweet Track elements

Two stakes (11, 32) lay at an oblique angle over the lower timbers, one either side of the trackway. They were supported by horizontal timbers (17 and 27) laid along the line of the track and probably represent paired roundwood stakes forming a cradle in which the walkway plank once rested. Stake 11 was dipping down to the ESE at an angle of c.30°, and stake 32 was dipping down to the WNW at the same inclination. This construction is like that known to the north, although the inclination of the stakes is less pronounced, possibly because the waters of the marsh were shallowing as they approached the island, and thus less height was needed to keep the walkway above the water.

Above the stakes were a series of radially split oak and ash offcuts (14, 21, 28, 49) aligned along the line of the trackway. Lying at right angles to these were more split ash plank fragments and offcuts (20, 22, 35, 43), a split hazel fragment (46) and a long hazel pole (47).

Figure 5. Sweet Track in Trench 1. Taken from the south. Scales 1 m

A mass of woodworking waste was present around the larger timbers mentioned above. The majority existed on the western side of the trackway, possibly testifying to the direction of whatever flow existed in the shallow waters of the reedswamp. On the eastern side of the structure the main items of note were a small oak splitting wedge (10) and a hazel woodchip (15).

The worked material on the western side, that was large enough to plan, included woodchips and woodworking waste/offcuts of ash (16, 18, 29, 37, 41, 42, 51, 57, 58), oak (19, 23, 24, 44, 45), hazel (30, 53) and birch (25). The smaller woodchips (103-157, 159) and pieces of bark (158, 160-163) were not planned. Amongst the mass of woodchips was a possible holly artefact (31). Further from the trackway structure were small pieces of hazel roundwood, both to the west (33, 36, 38, 39, 48, 50, 55, 54, 56, 57) and the east (12, 13) of the track line.

Two flint blades (small finds 1 and 2 on Figure 4b; Figure 6) were recovered from amongst the timber of the trackway.

Figure 6. Flint blades from Trench 1.

Woodworking

Apart from the woodchips and small offcuts, toolmarks were recorded on eight other pieces. The most significant of these were the two large roundwood stakes, which had well preserved cut ends.

Stake 11 was 58mm in diameter and survived to a length of 520mm. It had been cut to a chisel shaped point over the bottom 65mm, with five toolmarks in one plane and a single small cut on the opposing side. The surviving toolmarks were a maximum of 37mm wide and 18mm long, were concave across their width and had been cut at angles of 20-30°.

Stake 32 survived to a length of 505mm. It was 80mm in diameter and had been cut to a pencil shaped point over the bottom 360mm. Six toolmarks were present, showing cuts delivered at angles of 8-18°, producing flat to very slightly concave facets of maximum 45mm width and 90mm length. The top of the stake was in very poor condition, probably reflecting where rapid decay had occurred at the water/air interface during its active use. Between 200-260mm from the cut end the stake was compressed on one side where it had been pushed against one of the timber lying at right angles.

A small piece of radially split oak heartwood (10), 40mm long, 18mm wide and 11mm thick, may represent a broken wedge that could have been used to start the splitting process. It is crumpled at its wider end and crumpled and broken at its narrower end.

The possible holly artefact (31) was a poorly preserved but carefully shaped piece (31) of tangentially split holly, 210mm long, 34mm wide and 12mm thick. It retained the curvature of the parent log on its outer face but was cut flat on the inner face and had been carefully cut on its two radial sides. The piece showed no signs of obvious use, but this could have been due to its poor preservation. The deliberate shaping and the species of wood used, both suggest that it probably represents a small hand-held artefact, for an unknown purpose.

Four other pieces retained signs of woodworking (3, 74, 84, 98). Timber 3 was a 470mm long half split piece of hazel, that showed traces of a poorly preserved cut at one end. A 112mm long piece of roundwood (74), 18mm in diameter, showed possible traces of a worked end. The wood was poorly preserved because it had buckled in numerous places. This suggest that it might represent a small stake that had been driven in while still green and had buckled when the tip met a hard surface. A small piece of ash roundwood (98), 148mm long and 20mm in diameter, probably represents a small stake, as it had been driven in at an oblique angle and had a very poorly preserved chisel shaped cut end. Another piece of 23mm diameter ash roundwood (84), survived to a length of 112mm. At its wider end it had been cut to a chisel shaped point by an axe blow at an angle of 56°, leaving a facet 23mm wide and 10mm long.

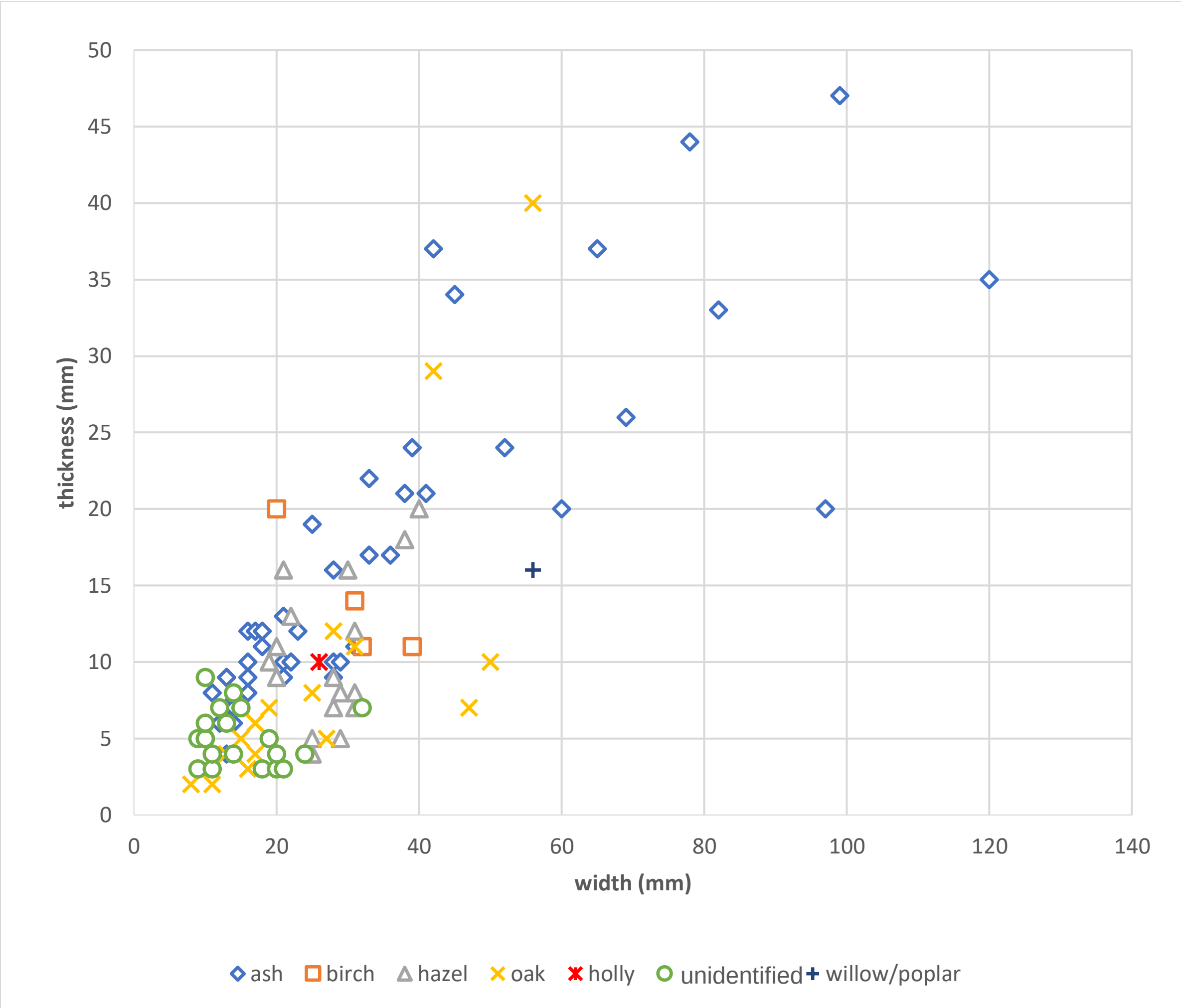

Figure 7. Sweet Track offcuts, woodchips and woodworking waste by species in Trench 1

The large number of woodchips and offcuts demonstrate that a lot of woodworking was taking place nearby. With the hazel, most of the woodchips could have been produced by cutting roundwood to length or to a point. Splitting of logs to produce planks was evident in the ash assemblage and to a lesser extent in the oak. Most of the splitting was radial, with a much smaller amount of tangential splitting, some of which may have been sub-division of large radially split timbers.

The wood chips have maximum lengths of 15-290 mm, widths of 8-50 mm and thickness of 2-22 mm. Very few complete facets survived on the woodchips and the offcuts. They had widths of 13-31 mm, lengths of 9-50 mm and had been cut at angles of 5-35°. The facet junctions were all clean rather than stepped and the facets were mainly flat across their widths with some examples that were slightly concave.

Plotting the widths and thickness of all the offcuts, woodchips and other woodworking waste from the Sweet Track in Trench 1 (Figure 7) shows that the chunkiest material is dominated by ash, with smaller numbers of oak, birch and hazel. The smaller woodchips are dominated by oak, with smaller numbers of ash. This suggests that only fine finishing of oak timbers was taking place in that location, in contrast to more substantial working of ash timbers. The relative lack of very small woodchips of hazel, birch, holly and willow/poplar may be an indication that no fine working of these species was taking place.

Species selection
Oak timbers were visually identified (by Brunning) and other species were identified microscopically by Dana Challinor.

The species composition of the wooden remains is dominated by hazel, oak and ash with isolated examples of holly, yew, birch and willow or poplar (Table 1, Figure 8). Hazel is the dominant species of the roundwood and was also used for the two larger stakes. It did not provide many of the split timbers. Most of the hazel woodchips were quite small and could have been produced by cutting roundwood to a length or to a point.

	Hazel	Ash	Oak	Holly	Yew	Birch	Willow or Poplar	Alder or hazel
Roundwood	13	5	-	1	-	-	-	2
Woodchips	17	32	14	1	-	3	-	-
Split timber	1	-	2		1	-	1	-
Stakes	2	16	-	-	-	-	-	-
Pegs	-	1	-	-	-	-	-	-
Artefacts	-	-	1	1	-	-	-	-
Total	33	54	17	3	1	3	1	2

Table 1. Species selection in the Sweet Track, Trench 1.

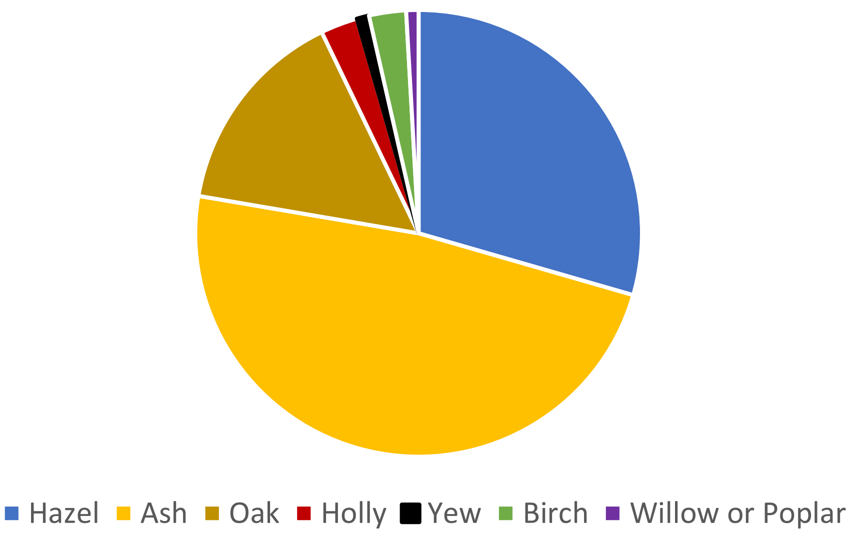

Figure 8. Species used in the Sweet Track in Trench 1.

Almost half the woodchips were ash and that species was also the most dominant in the split timber offcuts and small planks. Oak was present mainly in the form of woodchips, with only two split pieces. This suggests that these two large tree species were being split and cut to form planks.

Previous excavations of the Sweet Track by the Somerset Levels Project have included the species identification of over 2,500 samples (Orme and Coles 1985). The results show that oak and hazel were the most dominant species, with alder, ash, and holly also commonly used. Willow and poplar were occasionally used, but yew and birch were rarely selected. Hornbeam, dogwood, ivy, apple, lime and elm were also recorded occasionally or rarely. The species composition varied somewhat along the line of the trackway (ibid, table 3, p.16). Of the three most frequent species from Trench 1 (ash, hazel and oak), hazel is the most consistently used over the whole length of the structure, always being dominant or common. In contrast, ash is very variable, commonly used in some places but rare in others. Trench 1 is the only site along the track where it is the dominant species. A short distance to the south at the SWB site it was only occasionally used and to the north it was common on the SWC site. Oak was dominant at SWC but SWB was the only site where it was only occasionally selected.

This pattern demonstrates the variability in species use on different parts of the track, especially where it approaches dry land, where the reedswamp environment gave way to a fringing belt of fen carr. The trackway species selection in Trench 1 corresponds more closely to the SWC site to the north, than to the SWB site to the south. The structure of the trackway mirrors that pattern, suggesting that the environment in the Trench 1 location more closely resembled the reedswamp than the fen carr which fringed the island.

Post-Sweet Track stratigraphy

The stratigraphy was recorded in section beside the point where the monolith sample tins were taken (Figures 4c and 9). At the base, the remains of the Sweet Track were in a light brown peat containing numerous remains of reeds (23). Above this was a more amorphous peat (22) with roots and seeds and a particularly rooty layer at c.2 m OD. This was succeeded by another light brown peat containing both reeds, bog bean seeds, leaves and roots (mainly alder roots to judge from the distinctive colour)

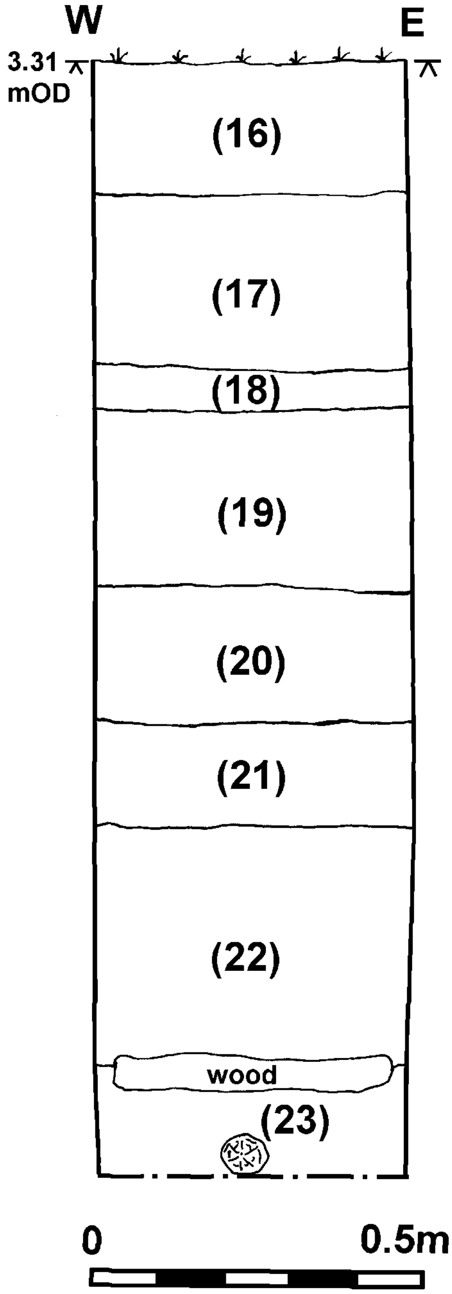

Figure 9. Section through Trench 1 deposits

(21). Worked wood existed at the base of this layer (see below).

That layer was succeeded by a soft light brown moss peat containing some very fine roots, resembling those of heather (20). Above this was a darker brown peat (19) with numerous small (non-arboreal) roots that were very dense in places. A light brown sedge peat (18) formed next, containing small roots as well as densely packed remains of sedge vegetation. Above this was a dark brown amorphous peat containing small wood fragments and tree roots (17). The top layer was a desiccated light brown, well laminated peat (16), which extended to the ground surface.

Figure 10. *Upper line of wood above Sweet Track, looking south. Trench 1. Scales 1 m*

Later worked material

After a layer of peat had covered the timbers of the Sweet Track, another burst of human activity is evidenced in wooden remains at 2.17-2.25 m OD (Figures 4. A, 9 and 10). Immediately above the line of the Sweet Track, two pieces of birch roundwood (6 and 7) were lying in the same orientation as the earlier trackway. They were poorly preserved and had been compressed to widths of 58 mm and 50 mm but were originally probably of c.35 mm diameter. Next to them were some short roundwood fragments, a small piece of bark (9) and a half-split piece of birch (8), 205mm long, 38mm wide and 3mm thick. North of this collection of wood was a mass of roots of an *in situ* tree bole of unknown species.

At the same level in the peat were numerous other pieces of bark and roundwood, 0.5-1.5 m further to the east, in addition to some patches of tree roots. One piece (3) was a half split hazel rod, 470 mm long, 37 mm wide and 5 mm thick, which may have been cut at one end, although the possible toolmark is not well preserved (Figure 11). Wood 5 was a roundwood hazel rod, 980 mm long and was probably originally c.25 mm in diameter. It had been cut at one end to a chisel point, with the tip broken off. The one definite and one probable cut ends were the only proof of human activity in the wood assemblage from this layer.

Radiocarbon dating of the cut rod (5) and one of the birch roundwood pieces (7) has shown that the activity they represent took place more than half a millennium after the Sweet Track was built (see below). This evidence for human activity directly above the line of the Sweet Track appears to be a remarkable coincidence, suggesting that although the trackway had been completely hidden by peat growth, its point of departure from Shapwick Burtle may have remained visible in some form on the island itself. A stone marker on the dry Burtle could have lasted that long but a living tree could also have perpetuated the line of the monument in local memory for part of that period. As the track was built through a dense reedswamp, it is conceivable that a tree on the dry ground at either end was used for sighting the route and perhaps they retained an association with the trackway and its ritual deposition long after the track itself had disappeared from sight.

Figure 11. Upper line of wood above Sweet Track (background) and cut pole (centre left), looking west. Trench 1. Scales 1 m

Radiocarbon Dating

Peter Marshall, Elaine Dunbar and Paula Reimer

Radiocarbon measurements were made on two samples from the worked wood above the Sweet Track in Trench 1. The sample dated at the Scottish Universities Environmental Research Centre was prepared to α-cellulose, combusted, graphitised, and dated by Accelerator Mass Spectrometry (AMS) as described by Dunbar et al (2016). The sample processed at 14CHRONO centre, Queen's University Belfast was dated as described by Reimer et al (2015). The δ13C values, relative to VPDB, were obtained by IRMS from the gas combusted for graphitisation. Internal quality assurance procedures and international inter-comparisons (Scott et al 2007; 2010) indicate no laboratory offsets and validate the measurement precision quoted.

The conventional radiocarbon ages reported for these samples, are listed in Table 2. The quoted errors are each laboratory's estimates of the total error in their dating systems.

Laboratory Number	Sample reference	Material	δ¹³C (‰)	Radiocarbon Age (BP)
OxA-35713	Wood 5	Wood unidentified, bark and last two rings	−28.7%±0.2	4493±32
UBA-34507	Wood 7	Wood unidentified, bark and last two rings	−27.9%±0.22	4522±29

Table 2: Sweet Track: Burtle Field radiocarbon results

The two measurements are statistically consistent at 95% confidence (T′=0.5; T′(5%)=3.8; v=1; Ward and Wilson 1978) and could therefore be of the same actual age. However, given there is no *a priori* evidence that they are the same actual age they have been combined using the OxCal function Combine (Acomb=101.1, An=50.0, n=2; Bronk Ramsey *et al* 2001) providing an estimate for the date of the structure of *3345–3100 cal BC* (*95% probability*; *Sweet Track: Burtle Field*; Figure 12).

The chronological modelling was undertaken using the program OxCal v4.2 (Bronk Ramsey, 2009; Bronk Ramsey and Lee 2013) and the atmospheric calibration curve for the northern hemisphere published by Reimer *et al* (2013). The algorithms used are defined exactly by the brackets and OxCal CQL2 keywords on the left-hand side of the technical graph which defines the model (http://c14.arch.ox.ac.uk/). The posterior density estimates output by the model are shown in black, with the unconstrained calibrated radiocarbon dates shown in outline. The other distributions correspond to aspects of the model.

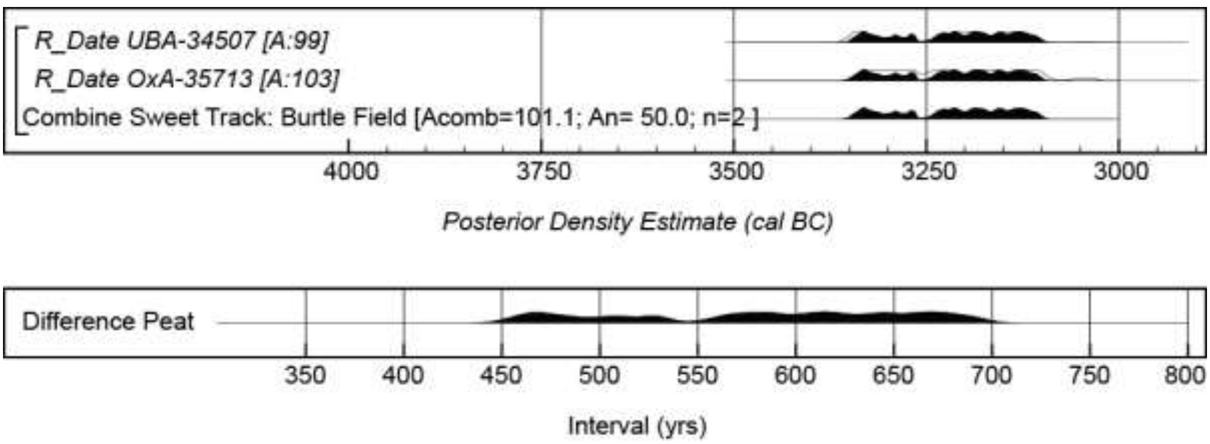

Figure 12: Probability distributions of dates from the Burtle Field structure, SWB Trench 1. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates, two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly. The bottom part of the figure shows the estimated interval between the Sweet Track and the later structure.

Figure 12 shows the time that elapsed between the use of the Sweet Track and the newly discovered structure – *450–540 years* (*30% probability*) or *555–700 years* (*65% probability*), probably *455–480 years* (*9% probability*) or *560–685 years* (*59% probability*). Given the vertical difference between the two structures is known (c.0.4 m) it is also possible to calculate the 'deposition time' (Bennett 1994, 337) for 10mm of peat to accumulate (Figure 13). The results are in line with other sequences from along the length of the Sweet Track and provided further *a priori* information to generate age-depth models for the area (Farrell *et al* 2019) using software such as Bacon (Blaauw and Christen 2011).

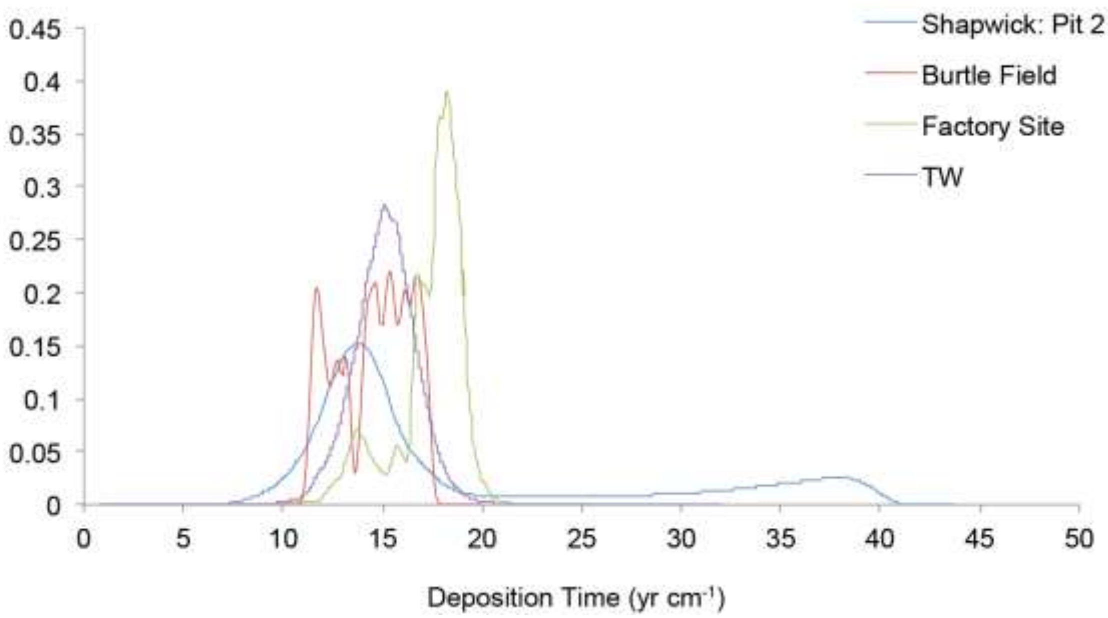

Figure 13: Deposition Time (DT) estimates for selected sequences along the Sweet Track

Trench 2

Trench 2 was located at the proposed junction of compartments A and B (Figure 3). It was 2 m x 3 m in size. The lowest deposit was a moss peat (15) ending at c.0.7 m below ground. Above this was a laminated woody peat (14) containing numerous roots (Figure 14). That layer extended to within 100 mm of the ground surface where it was capped by a dry dark brown amorphous peat (13). The ground surface was at 3.58–3.6 m OD.

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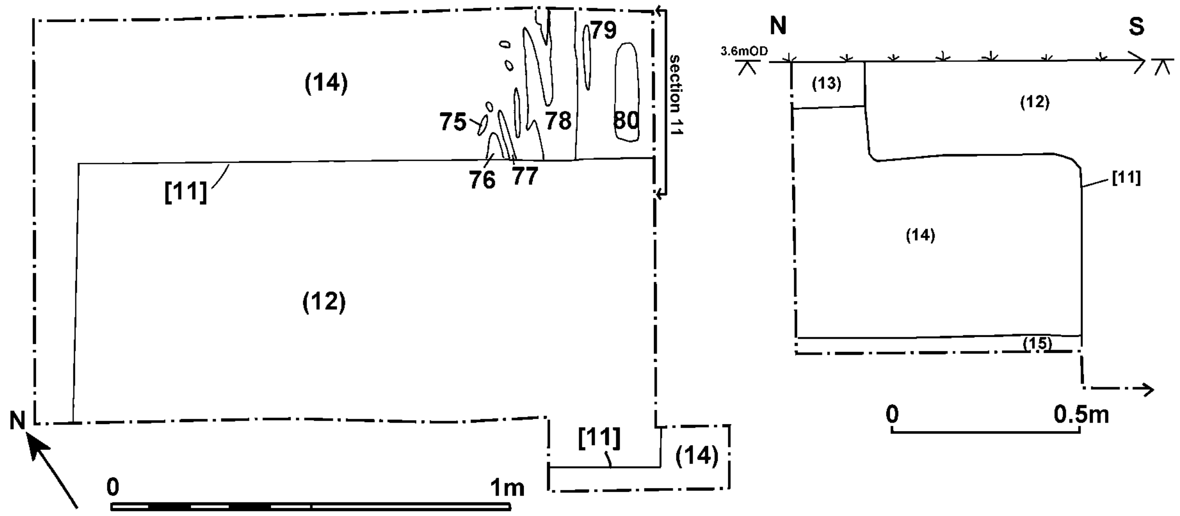

Figure 14. Plan and section of Trench 2

These natural layers had been cut through [11] by a trench 1.5 m wide, 3 m long and at least 0.8 m deep, with a shallow stepped extension on the northern side 0.5 m wide and 0.25 m deep (Figure 14). It was filled with a dark brown peat (12) that had been previously excavated and then backfilled. The orientation and dimensions of the trench allow it to be positively identified as the second southernmost trench of four that the Somerset Levels Project excavated at SWB in 1971 (Figure 2).

Figure 15. Trench 2. Upper wood cut by SLP on the left. Looking west. Scales 1m and 40 cm

As the slight remains of the trackway had already been excavated in this area, there was no need to take the trench any further down. The identification of this trench has allowed the positions of the other SLP trenches at the SWB site to be accurately plotted (Figure 3).

At 2.83–2.90 m OD an isolated patch of wood was recorded to the north of the SLP trench, orientated in the same direction as the Sweet Track over a width of 0.8 m (Figure 15). It consisted of several pieces of bark (75, 76, 78, 79) and two poorly preserved and compressed pieces of ash and alder or birch roundwood (77, 80). The wood was in a very poor condition and there were no clear toolmarks, but there is a possibility that the material could represent the remains of a simple trackway, on a similar alignment to the earlier Sweet Track. The SLP trench removed any southwards extension of the feature within Trench 2.

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Trench 3

Trench 3 was located at the intended southern end of the compartments (Figure 3). It was 2 m by 1.5 m in size. The ground surface and all the deposits within the trench sloped downwards to the north, away from the top of the island to the south (Figures 16 and 17).

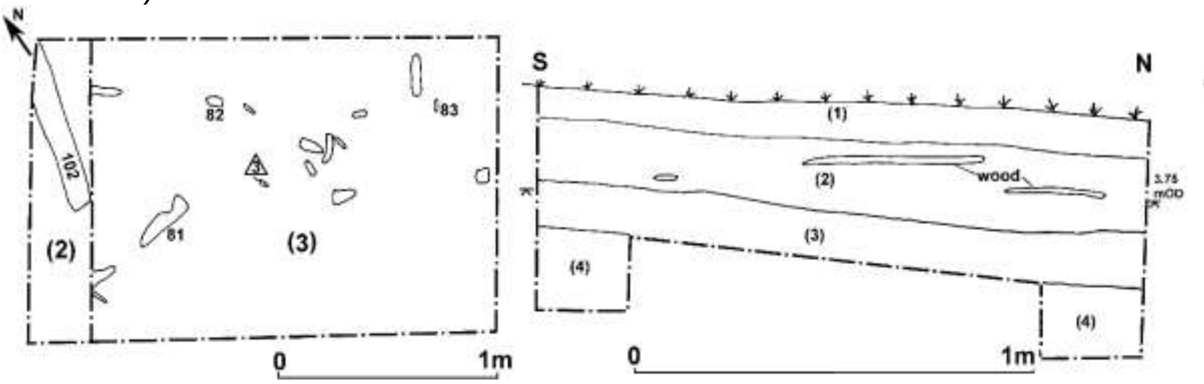


Figure 16. Plan and section of Trench 3

At a depth of 0.35-0.40m below the surface (3.53-3.67 m OD) was a light grey sand (4) with yellow patches and occasional charcoal flecks (Figures 15 and 16). This represents the Burtle sand bed on the island. Above this was a c.120 mm thick dark

Figure 17. Trench 3. Weathered surface of Burtle sand despoit. Looking west. Scales 1m

greyish brown silty sand (3), possibly representing hillwash and erosion of the sand bed. A small flint microlith (SF2) was recovered from the interface of the two layers at 3.63 m OD (Fig. 18). At a similar level were a few small fragments of poorly preserved wood (81, 82, 83) and some roots penetrating into the sand below.

This eroded sand was covered by a very dark brown dry amorphous peat (2) 160-180 mm thick between 3.67 and 3.93 m OD (Figure 15). Within the peat was a very dried and badly preserved piece of yew (102), 35 mm wide, 24 mm thick and over 900 mm long, which had modern roots growing through it. It was a radially split piece, but there were no clear toolmarks. Yew trees have been recorded amongst samples taken from the bog oaks around Shapwick Burtle for dendrochronological dating (Cathy Tyers pers comm.). The peat was covered by a 100 mm thick black amorphous dry peaty topsoil (1) with the ground surface dropping south to north from 4.02 m to 3.95 m OD.

As the peat was very thin in this location, and there was little stratigraphy above the sand, it was decided to move the end of the compartment further north. For this reason, a fourth trench was excavated.

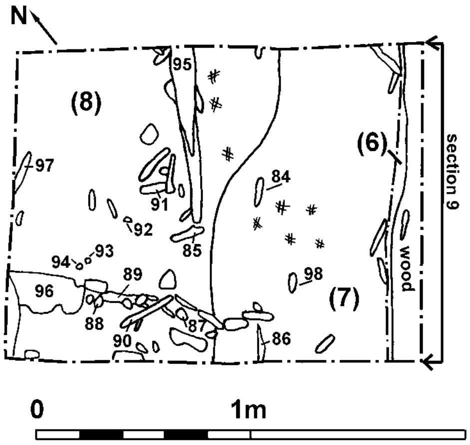
Figure 18. Trench 3. Microlith

Trench 4

Trench 4 was located where the southern edge of the membrane would cross the Sweet Track. It was 2m x 1.5m in size. The lowest context was a greenish-grey silty clay (10) that had some roots penetrating from layers above (Figures 19 and 20). It was at least 200mm thick. The top of the layer sloped down northwards away from the island from 2.83 m OD to 2.93 m OD. Above this was a 30-100 mm thick deposit of dark greyish brown sandy silt (9) containing numerous small pieces of wood at the interface with layer 10. It sloped downwards and thinned to the north as it went away from the island. This probably represents a layer of hillwash from the Burtle.

The sandy silt was sealed by a very dark brown silty peat (8) containing numerous twigs and roots. Unlike the underlying layers its upper surface was level (at 2.93 m OD), covering the sandy silt to a depth of 170 mm at the northern side of the trench but tapering to almost nothing at the southern end. On the eastern half of the trench the silty peat was overlain by a very dark greyish brown organic silty mud (7), up to 100 mm thick.

Layers 7 and 8 both contained charcoal flecks and numerous pieces of wood. Context 7 contained some small pieces of ash and alder or hazel, one of which (84) was a 23mm diameter rod that had been cut at one end leaving a chisel shaped point. The blow had been delivered at a point where the stem was widening and curving slightly. That form would be consistent with the removal of a coppiced stem at the 'heel'.



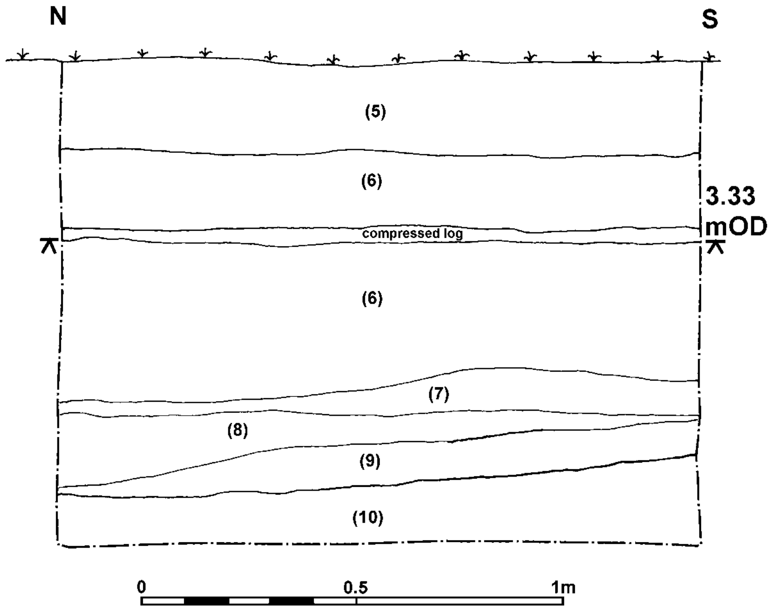


Figure 19. Plan and section of Trench 4.

Figure 20. Trench 4. West facing section. Scale 1 m

Context 8 contained numerous fragments of ash and alder wood and several pieces of bark, in addition to a quarter split log (95), 860 mm long by 120 mm by 130 mm. Another fragment of unidentifiable species (94), 71 mm long by 18 mm by 12 mm, had been cut at one end to form a chisel shaped point. The piece had been tangentially split, possibly a secondary reduction of a larger radially split timber, and was set almost vertically, possibly as a small peg.

The charcoal and worked wood in layers 7 and 8 suggest that human activity was taking place in that area, although not forming a coherent structure. They are considerably higher than the Sweet Track in the SWB area and in Trench 4. The dating evidence from pits 1 and 2 of the Mesolithic of the wetland/dryland edge in the Somerset Levels project, a short distance to the east in the same field, also suggest that remains this close to the surface are probably significantly later than the Sweet Track (Bell *et al* 2015, 127-137).

A dark brown dry peat (6) containing numerous roots and twigs, overlay contexts 7 and 8. It was 0.50-0.59 m thick, the upper surface being at 3.53 m OD. Near the top of this layer was a half split ash log (101) at 3.33 m OD, running completely across the trench. It was 160 mm in diameter.

The upper layer was a black, dry amorphous peat, roughly 200 mm thick. The ground surface was at 3.64-3.75 m OD.

5. WOOD CONDITION ANALYSIS

Dr Eleanor Schofield and David Pearson

Samples

Samples arrived in two layers of plastic zip lock bags. Initial observations regarding the number of pieces the sample comprised of, size and weight were recorded and can be seen in Table 3. Where samples had more than one piece these were recorded as A or B, and this nomenclature was used in subsequent analysis.

Table 3: Number of pieces in each sample, dimensions and weights

Sample ID	Species	Number of pieces	length x diameter OR length x width x height (mm)	Weight (g)
11	Hazel	2	120 x 60, 80 x 55	444.8
17	Holy	1	140 x 75	704.9
27	Ash	1	135 x 100 x 75	1009.7
32	Hazel	1	115 x 60	442.4
34	Ash	1	130 x 80	805.6
36	Hazel	1	100 x 90	750.8
47	Hazel	2	140 x 55 x 25; 115 x 50 x 25	315.4
84	Ash	1	70 x 30 x 20	63.9
95	unknown	1	135 x 110	1352.6
102	Yew	2	135 x 35 x 15; 80 x 30 x 10	126.0

Visual assessment

For each sample the initial wood was inspected in terms of colour, saturation, firmness, mould, smell and a pin test was conducted. The pin test involves the insertion of a 30 mm metal pin in to the material and measuring how far it can progress without hindrance. Where the different grain orientations can be distinguished, the pin is tested in each to see if there is any variation. The information is recorded in Table 4.

Table 4. Visual observations on colour, texture and pin test

Sample ID	Visual observations	Pin test
11A	Very spongey, dark brown, small amount of bark attached, saturated, soft on surface, no obvious smell, no mould	Pin inserts with no resistance
11B	Very spongey, dark brown, small amount of bark, saturated, not as soft as 11A, no obvious smell, no mould	Pin inserts with no resistance
17	Very spongey, dark brown, no obvious soft areas, saturated, no obvious smell, no mould	Pin inserts with no resistance
27	Spongey, dark brown, soft, saturated, no obvious smell, no mould	Pin inserts, but with a small amount of resistance in comparison to the other sample.
32	Sample fell apart on removing from bag. Very spongey, dark brown, very soft, saturated, no obvious smell, no mould	Pin inserts with no resistance
34	Not spongey, dark brown, fairly firm, saturated, no obvious smell, no mould	Pin inserts with no resistance
36	Slightly spongey, dark brown, fairly firm, saturated, no obvious smell, no mould	Pin inserts, but with a small amount of resistance in comparison to the other sample.
47A	Very spongey, soft, saturated, dark brown, no smell, no mould	Pin inserts with no resistance

47B	Split into two parts on removal from bag Very spongey, dark brown, very soft, saturated, no smell, no mould	Pin inserts, but some resistance
84	Slightly spongey, dark brown, fairly firm, saturated, no smell, no mould,	Pin inserts all the way radially, but does not go all the way tangentially
95	Spongey, dark brown, soft in places but not throughout, saturated, no smell, no mould, bit of bark remains	Pin inserts, but some resistance
102A	Spongey, dark brown, not saturated (damp), firm, no smell, no mould	Pin inserts, but some resistance
102B	Spongey, dark brown, not saturated (damp), firm, no smell, no mould	Pin does not fully insert

No obvious smell was observed when opening any of the packets, and no mould was visible on any of the samples. All samples were saturated apart from 102 A and B. All samples had a spongey texture, in that compression of the sample could result in movement. Just over half of the samples were soft, therefore when compression was applied, the material did not go back to its original shape. The remaining samples were firm and visible damage was not induced when applying a force. In most cases the 30 mm pin went into the wood with no resistance. In a few instances there was some resistance and occasionally did not go in all the way, indicating some greater wood integrity in these areas.

Physical properties

Initial attempts were taken to remove a core sample, but this was not possible due to the lack of structural integrity of the wood. Therefore, sections of wood were taken from the sample and used for analysis. Once sectioned, the weight of each sample was recorded. They were then dried for 24 hours at a temperature of 100 ^{o}C to ensure all moisture is removed. Following drying, the weight of the section is again recorded. The moisture content (%) is then determined using the following equation:
moisture content (%) = 100 x (M_s – M_o)/M_o
Where, M_s is the mass of waterlogged wood and M_o is the mass of oven dried wood.

To measure the basic density of the samples, cube sections were cut and the volume was calculated. The sections were then dried following the same procedure used to determine the moisture content. The basic density was then calculated using the following equation:
basic density, Db (g/cm3) = M_o / V_s
Where, V_s is the volume of the sample when wet

The residual basic density compares the basic density of the archaeological sample to that of nondegraded (fresh) wood from the literature. It is calculated using the following equation:
residual basic density = 100 x (D_b / D_{bf}),
Where, D_{bf} is the basic density of fresh wood. A value of 0.7 g/cm3 as this is representative of both ash and oak samples.

The loss of wood substance can then be calculated using the following equation:
loss of wood substance (%) = 100 x (D_b – D_{bf})/D_{bf} The results from this testing can be seen in Table 5.

Table 5. Moisture content, (residual) basic density and lack of wood substance

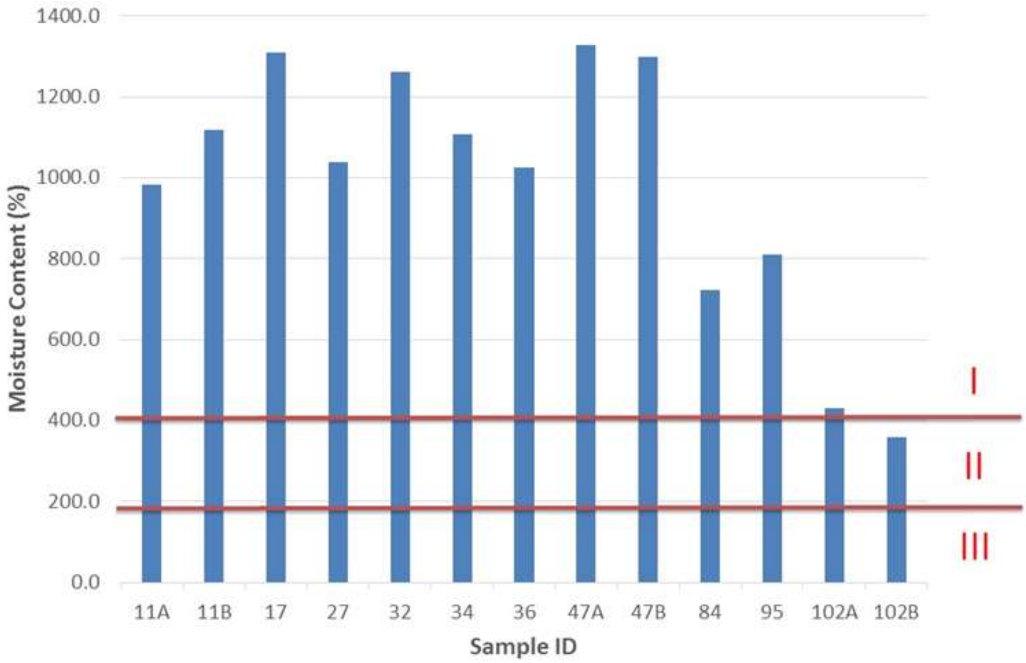
Sample ID	Wet weight (g)	Measure ments (cm)	Measure ments (cm)	Measure ments (cm)	Volume (cm^3)	Dry weight (g)	Moisture Content (%)	Basic Density of Sample (g/cm3)	Residual Basic Density (%)	Loss of Wood Substance (%)
11A	1.06	1.03	1.04	1.14	1.22	0.098	981.6	0.080	11.5	88.5
11B	0.998	0.95	0.93	1.15	1.02	0.082	1117.1	0.081	11.5	88.5
17	1.099	0.91	1.03	1.15	1.08	0.078	1309.0	0.072	10.3	89.7
27	0.911	0.81	0.95	1.13	0.87	0.08	1038.8	0.092	13.1	86.9
32	1.061	0.99	0.96	1.17	1.11	0.078	1260.3	0.070	10.0	90.0
34	1.388	1.16	1.05	1.35	1.64	0.115	1107.0	0.070	10.0	90.0
36	1.776	1.28	1.16	1.25	1.86	0.158	1024.1	0.085	12.2	87.8
47A	0.6	0.92	0.93	0.88	0.75	0.042	1328.6	0.056	8.0	92.0
47B	0.531	0.75	0.97	1.03	0.75	0.038	1297.4	0.051	7.2	92.8
84	1.153	0.97	1.11	1.15	1.24	0.14	723.6	0.113	16.2	83.8
95	1.502	1.06	1.1	1.23	1.43	0.165	810.3	0.115	16.4	83.6
102A	1.247	0.96	0.95	1.29	1.18	0.235	430.6	0.200	28.5	71.5
102B	0.993	1.06	0.83	1.17	1.03	0.217	357.6	0.211	30.1	69.9

The De Jong classification indicates the degree of degradation of archaeological wood, as indicated by the moisture content. There are three classes which are defined as follows:

- Class III is wood containing < 185 % water = sound core beneath a thin degraded layer
- Class II is wood containing 185 – 400 %water = Comparatively small core present
- Class I is > 400 % water = highly degraded wood predominates

The moisture content for the Sweet Track samples, with indicative lines of the different wood classes as defined by De Jong can be seen in Figure 21. In all but one of the samples, highly degraded wood (Class I) dominates. The average moisture content is 983%, with a maximum of 1238 % and minimum of 357%.

Figure 21. Moisture content of samples, compared with De Jong wood degradation classification



The basic density of fresh oak is in the region of 0.7 g/cm^3. In all the Sweet Track samples there is significant decrease in the density, with residual basic densities in the order of 10-20 % of fresh oak. This corresponds to an average loss of wood substance of 85 %, with a range of 70 – 92 %, as can be seen in Figure 22.

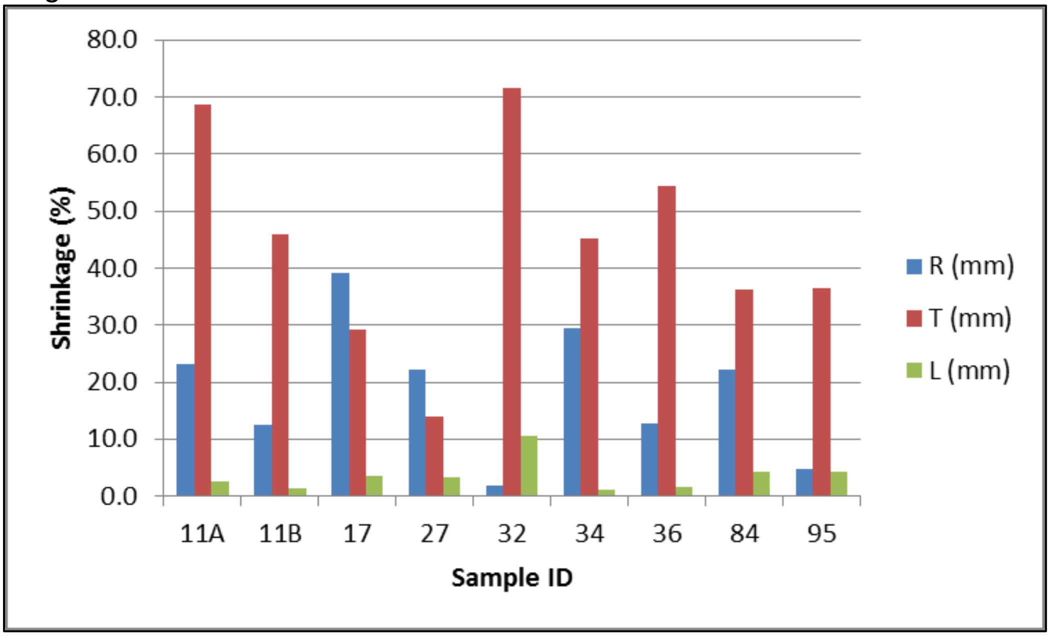
Figure 22. Residual Basic Density and Lack of Wood Substance

The shrinkage was measured by sectioning samples (approximately 1 cm^3) and inserting pins to define the longitudinal, radial and tangential directions. Distances were measured between the points when the wood was saturated. After drying for 24 hours at 100 °C the distance was re-measured and percentage shrinkage was determined for each direction. The recorded measurements and the associated percentage shrinkage in the radial, tangential and longitudinal direction can be seen in Table 6 and Figure 23.

Table 6. Shrinkage values and percent changed in radial, tangential and longitudinal directions

Sample ID	Saturated			Dry (100 °C for 24 hrs)			% Shrinkage		
	R (mm)	T (mm)	L (mm)	R (mm)	T (mm)	L (mm)	R (mm)	T (mm)	L (mm)
11A	11.2	11.5	31.1	8.6	3.6	30.3	23.2	68.7	2.6
11B	10.4	8.7	27.6	9.1	4.7	27.2	12.5	46.0	1.4
17	13.39	12.58	12.97	8.14	8.92	12.5	39.2	29.1	3.6
27	10.4	9.4	33	8.1	8.1	31.9	22.1	13.8	3.3
32	8.74	10.89	18.1	8.58	3.1	16.18	1.8	71.5	10.6
34	10.2	8.2	27.2	7.2	4.5	26.9	29.4	45.1	1.1
36	10.2	4.6	26.1	8.9	2.1	25.7	12.7	54.3	1.5
84	9.9	9.4	32.2	7.7	6	30.8	22.2	36.2	4.3
95	12.7	11	41.3	12.1	7	39.5	4.7	36.4	4.4

Figure 23. Shrinkage as percentage of original length in the radial, tangential and longitudinal directions



In all cases, the minimum observed shrinkage was in the longitudinal direction, expected. The maximum shrinkage in the longitudinal was 10.6 %, the minimum was 1.1% and the average was 3.7

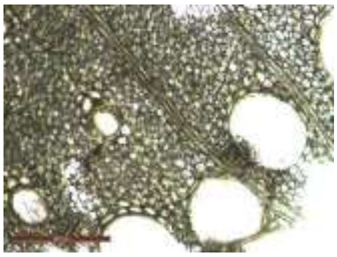
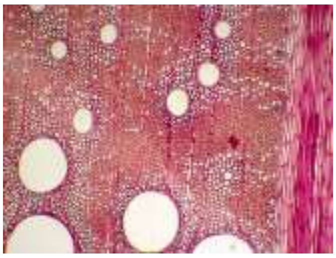
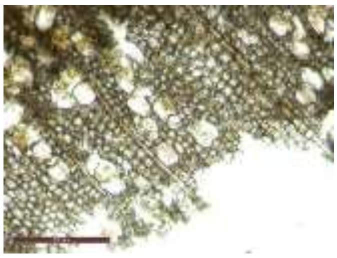
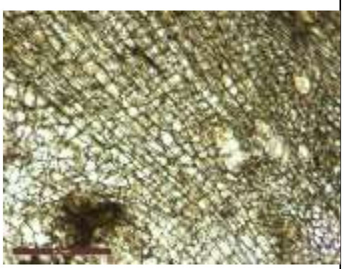
%. Shrinkage between the samples for the other directions varied quite drastically, from one sample to another. In the radial direction there was a maximum of 39.2 %, a minimum of 1.8 % and an average of 18.7 %, and in the tangential there was a maximum of 71.5 %, a minimum of 13.8 % and an average of 44.6 %.

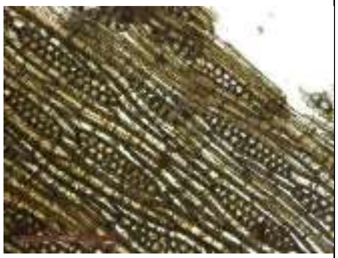
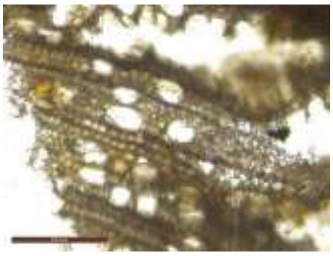
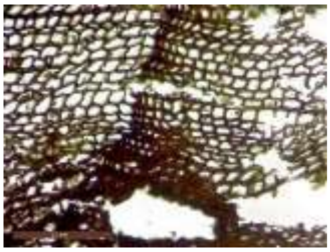
Microscopy

Light microscopy

Samples were prepared by soaking in water and using a single or double edged razor to create a thin section, in order for the light to effectively penetrate the sample. Images were taken on a Leica DMLM Microscope, using a DFC 290 camera and LAS v4 software. Some samples were too soft and spongy to get a good, thin section, making it impossible to get a good image using this technique. The images of the samples taken and those of fresh oak and ask are given in Figure 24.

Figure 24. Light microscopy images

Sample	**Transverse section**		**Sample**	**Transverse section**
Fresh Ash			34	
Fresh Oak			36	
11			47	Not available
17			84	Not available

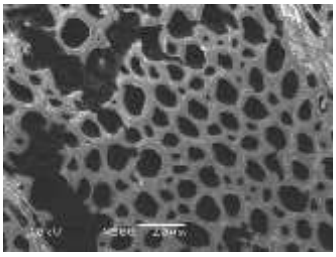
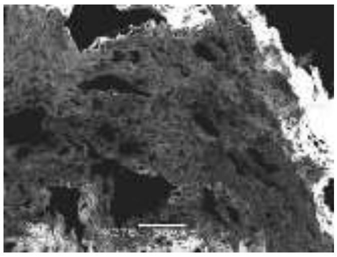
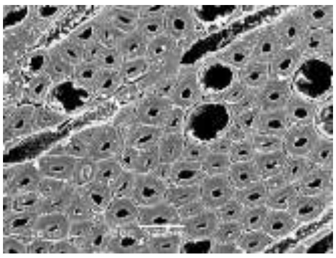
27	Not available		95	
32			102	

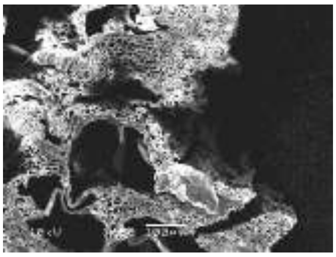
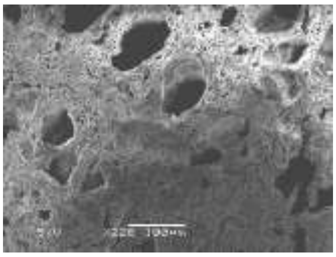
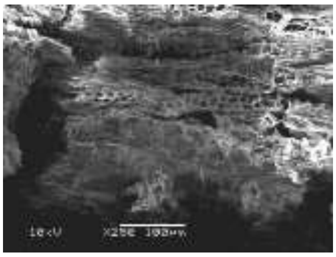
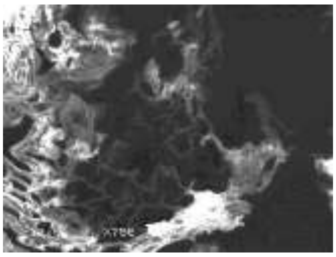
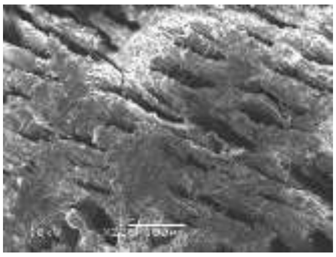
The images show that whilst there is some structural integrity left, there is loss of cell wall material, which has resulted in some collapse and distortion of the structure.

Scanning Electron Microscopy analysis

Samples were sectioned to approximately 0.5 cm^3 pieces and loaded onto Aluminium stubs using carbon tape. Images were taken on a JEOL 5510. Images of the samples, compared with that of fresh oak and ask can be seen in Figure 25

Figure 25. Scanning Electron Microscopy Images (x220 magnification)

Sample	**Transverse section**	**Sample**	**Transverse section**
Fresh Ash		34	
Fresh Oak		36	Not available

11	Not available	47	
17	Not available	84	
27		95	
32		102	Not available

Obtaining sections suitable for analysis with this technique was extremely challenging due to the heavy degradation of the wood. Sectioning resulted in distortion of the wood that can be seen by the elongated vessels and crushed structure in the micrographs above. Regardless, as with the light microscope images, it is clear that cell wall material has been lost.

X-ray Fluorescence analysis

X-ray Fluorescence (XRF) analysis was completed using an Oxford Instruments XMET8000. Sections of the sample, approximately 0.5 cm^3 in size were analysed. Three sections from each sample were analysed for a total of 120 seconds. The XRF was calibrated to analyse the elements listed below by measuring known quantities of iron and sulphur in pellets of cellulose. The results, compared with that of fresh oak and ash, are given as bar chart format in Figure 26 and actual numbers in Table 7.

Figure 26. Contents in ppm of Ca, S and Fe of samples compared with fresh oak and ash

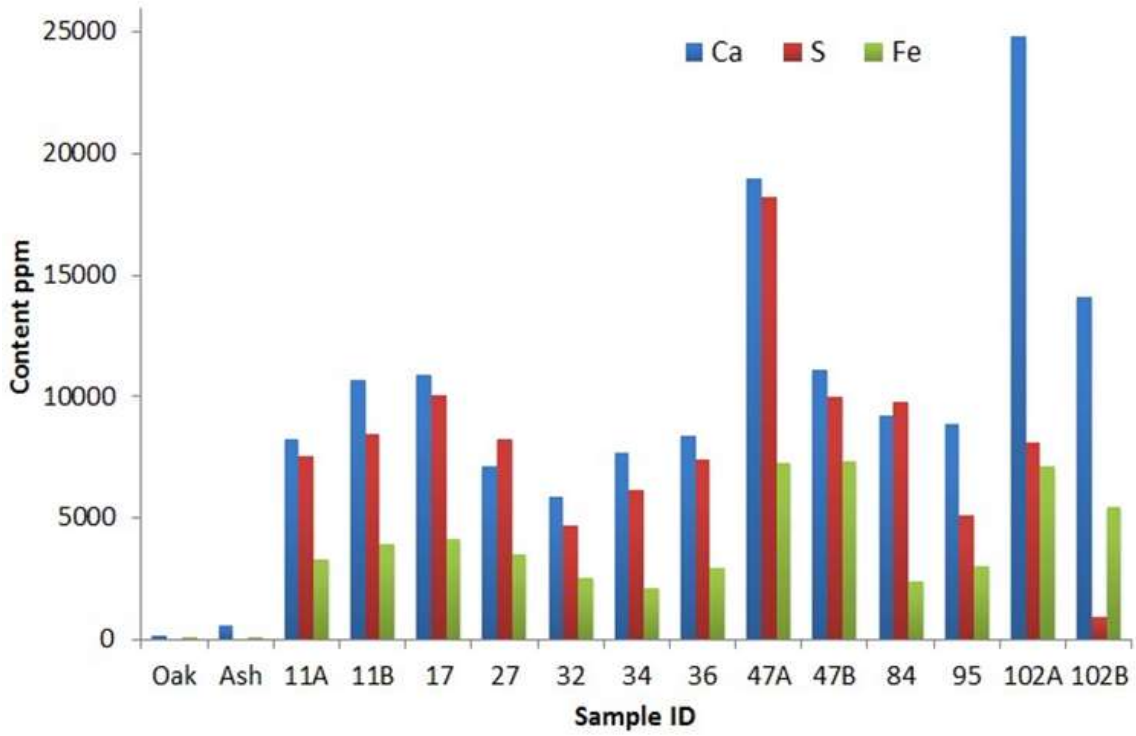


Table 7. Contents in ppm of Ca, S and Fe of samples compared with fresh oak and ash

	Ca (ppm)	S (ppm)	Fe (ppm)
Oak	137		19
Ash	600		15
11A	8274	7549	3283
11B	10712	8452	3919
17	10923	10082	4112
27	7113	8241	3506
32	5905	4717	2500
34	7679	6137	2094
36	8371	7400	2948
47A	18949	18208	7237
47B	11093	9992	7328
84	9196	9755	2374
95	8845	5121	2986
102A	24861	8081	7111
102B	14095	957	5483

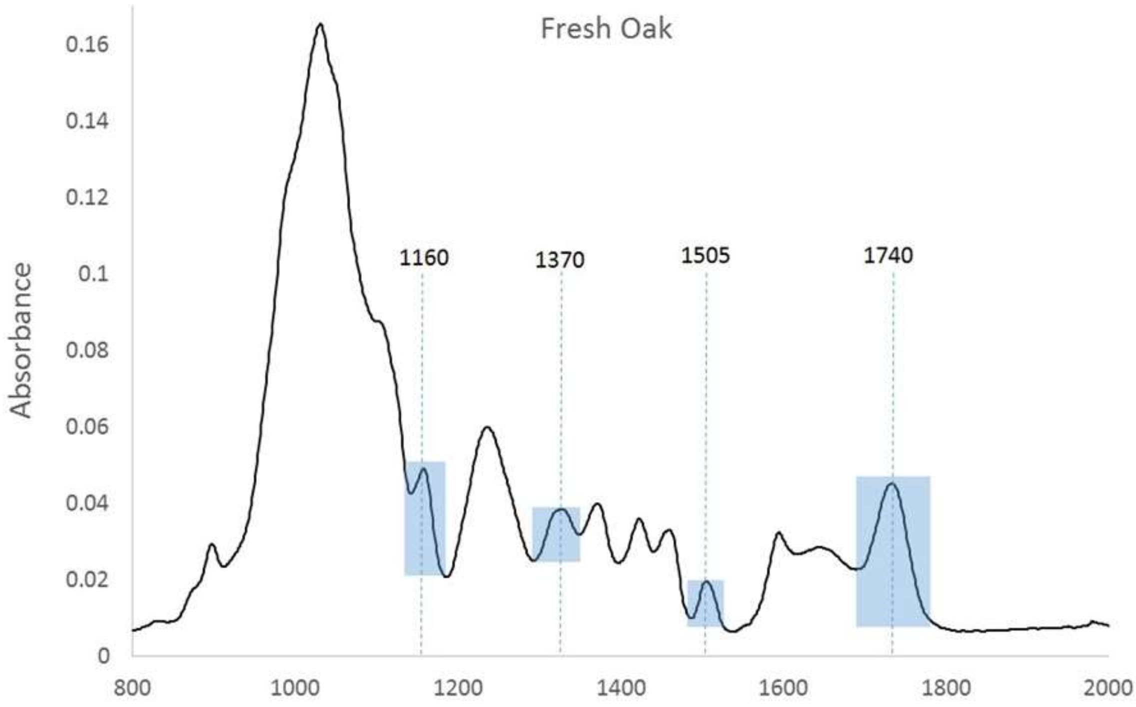
Both fresh oak and ash were found to contain minimal levels of calcium and iron and no sulphur. The samples contained significantly higher values. Calcium content was a minimum of 5905 ppm, a maximum of 24861 ppm and an average of 11233 ppm.

Sulphur was a minimum of 957 ppm, a maximum of 18208 ppm and an average of 8053 ppm. Iron was a minimum of 2094 ppm, a maximum of 7328 ppm and an average of 4221 ppm. The presence of these elements at these concentrations will be due to the prolonged exposure to the peat and the increased pathways into the wood structure as degradation progresses. The presence of sulphur and iron can cause problems in archaeological wood if the sulphur oxidises and forms problematic acidic compounds which can break down the wood components.

Fourier Transform Infrared Spectroscopy analysis

Thin sections of wood were taken from each sample using a double edged razor blade. Spectra were collected using a Perkin-Elmer Spectrum One Fourier Transform Infrared Spectrometer. 32 scans were collected on each sample with a resolution of 4 cm^{-1}. Fresh oak and ash samples were measured for direct comparison in the analysis

Figure 27. FTIR spectra of fresh oak indicating key peaks used in analysis

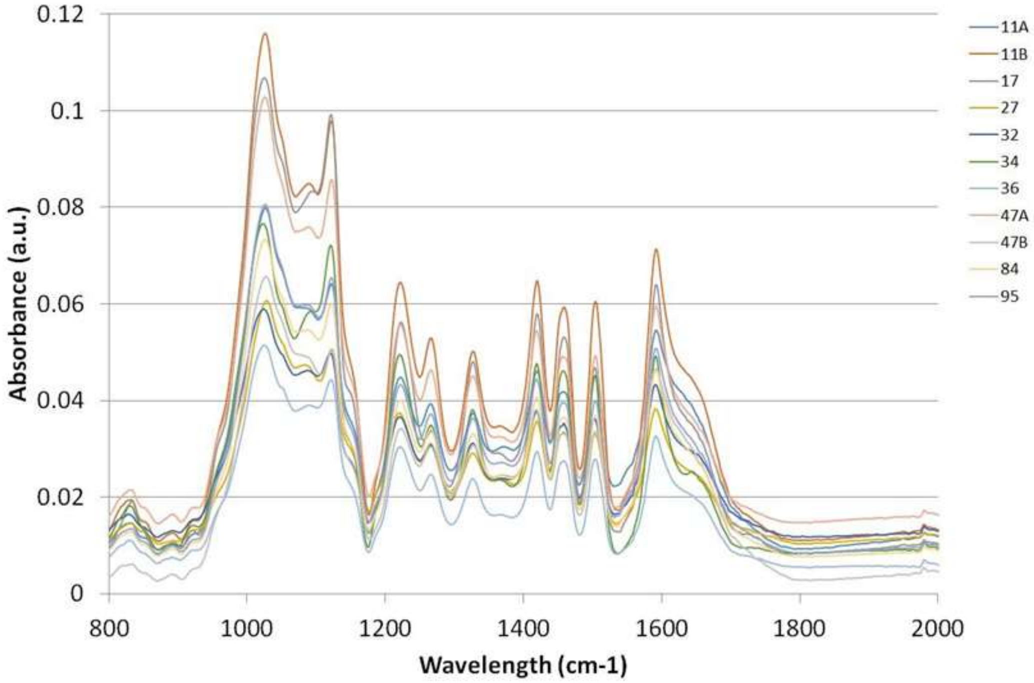


Wavelength cm^{-1}

Data was analysed by looking at key peaks in the data that can be associated with specific bonds within the wood, namely 1160 cm^{-1} (C-O-C vibration in hemicellulose and cellulose), 1370 cm^{-1} (CH deformation in hemicellulose and cellulose), 1505 cm^{-1} (Aromatic skeletal in lignin), and 1740 cm1 (C=O in hemicellulose), as seen in Figure 27.

The FT-IR data for the samples can be seen in Figure 27. The data are offset to make them distinguishable from each other. In all cases the peak at 1740 could not be observed, indicating a complete loss of hemicellulose. The peaks at 1160 and 1375 are therefore attributed to cellulose.

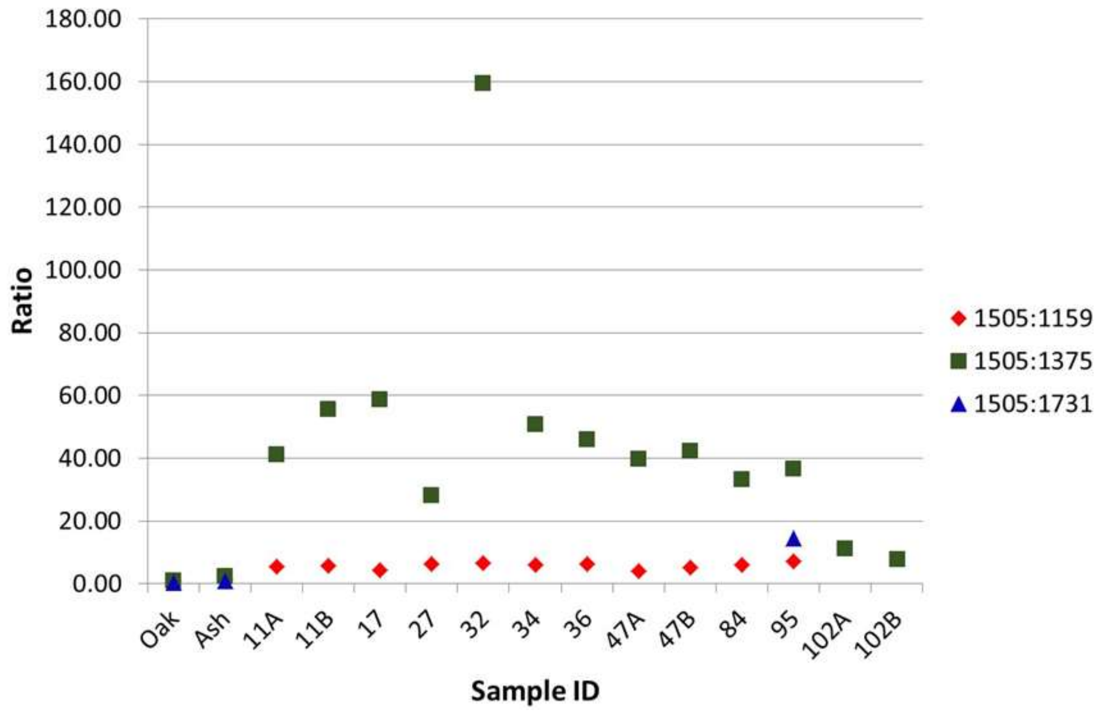
Figure 28. FTIR data of samples



Traditionally in wood, the holocelluose components (hemicellulose/cellulose) are lost before the lignin. Therefore, by measuring the ratio of the lignin peaks to that of the holocellulose components for fresh wood and then comparing with the archaeological samples, gives us an indication of how degraded the material is. This data can be seen in Figure 29. Where no ratio is given, this is due to there being insufficient peak available to measure, indicating a complete lack of that material component from the wood.

In all cases, the ratio for the Sweet Track samples is greater than that for the fresh oak and ash. This is most pronounced for the 1505:1375 ratio, where the majority of the samples have a ratio in the region of 50 times more than the fresh wood. An exception to this is sample 32, which shows a ratio of 160 times more than the fresh wood. This concurs with the visible inspection which listed it as very spongey and that it fell to pieces on removal from the storage bag, and that this sample had the largest shrinkage in the longitudinal and tangential directions. The other exception is sample 102 (A and B), which show less degradation that the rest of the sample set. This concurs with the lower moisture content measured for them and the resistance observed when the pin test was completed.

Figure 29. Ratios of Lignin to holocellulose components



Conclusions

The samples provided consist of heavily degraded wood. If not kept wet, shrinkage, distortion, cracking and ultimately complete breakdown of the wood will occur.

6. MONITORING

Henning Matthiesen (National Museum of Denmark) and Ian Panter (York Archaeological Trust)

Introduction

The purpose of the horizontal membrane (as described earlier in this report) is to reduce the loss of water through evapotranspiration, and it has a slight downwards slope towards the middle, where it is perforated to allow rainwater to infiltrate to the trackway. This should locally raise the water level, or at least the moisture content of the soil, and thereby reduce the oxygen access to the trackway. Oxygen is probably the single most important factor when it comes to the degradation of wood, and reducing the access of oxygen is beneficial to the preservation conditions.

A monitoring program has been set up to document the effects of the membrane. This consists of logging of the groundwater level underneath and outside the membrane, and has been carried out by Ian Panter from York Archaeological Trust. Furthermore, measurement of oxygen concentrations and logging of the water content and temperature are used to investigate the conditions below and above the groundwater level. The theory and principles behind the latter measurements are described in Matthiesen et al. (2016).

Methods

The installation of the membrane had been previously described in this report.. Installation of the equipment took place on the 29th-30th March 2017 in the presence of Richard Brunning (South West Heritage Trust), Ian Panter (York Archaeological Trust), Jim Williams and Hayley McParland (Historic England), Kirsty High (University of York), a drilling operator (Contractor), and Henning Matthiesen (National Museum of Denmark).

Eight dipwells were installed in two rows (A1-A4 and B1-B4) across the plastic membrane (figure 31). Next to three of these dipwells (A1, A2 and B2) sensors for monitoring oxygen, temperature and moisture content in the peat were installed. In addition, a small test pit was dug in order to take samples for measuring the porosity and the reactivity of the soil, and to measure pH, water content and conductivity in situ; the test pit was dug at some distance from the trackway in order to avoid unnecessary disturbance of the trackway itself (figure 30).

Figure 30. Oxygen and temperature sensors were installed from the soil surface through a removable installation tube (left). A small test pit was dug outside the membrane covered area to take ring samples of soil for porosity measurements (right)

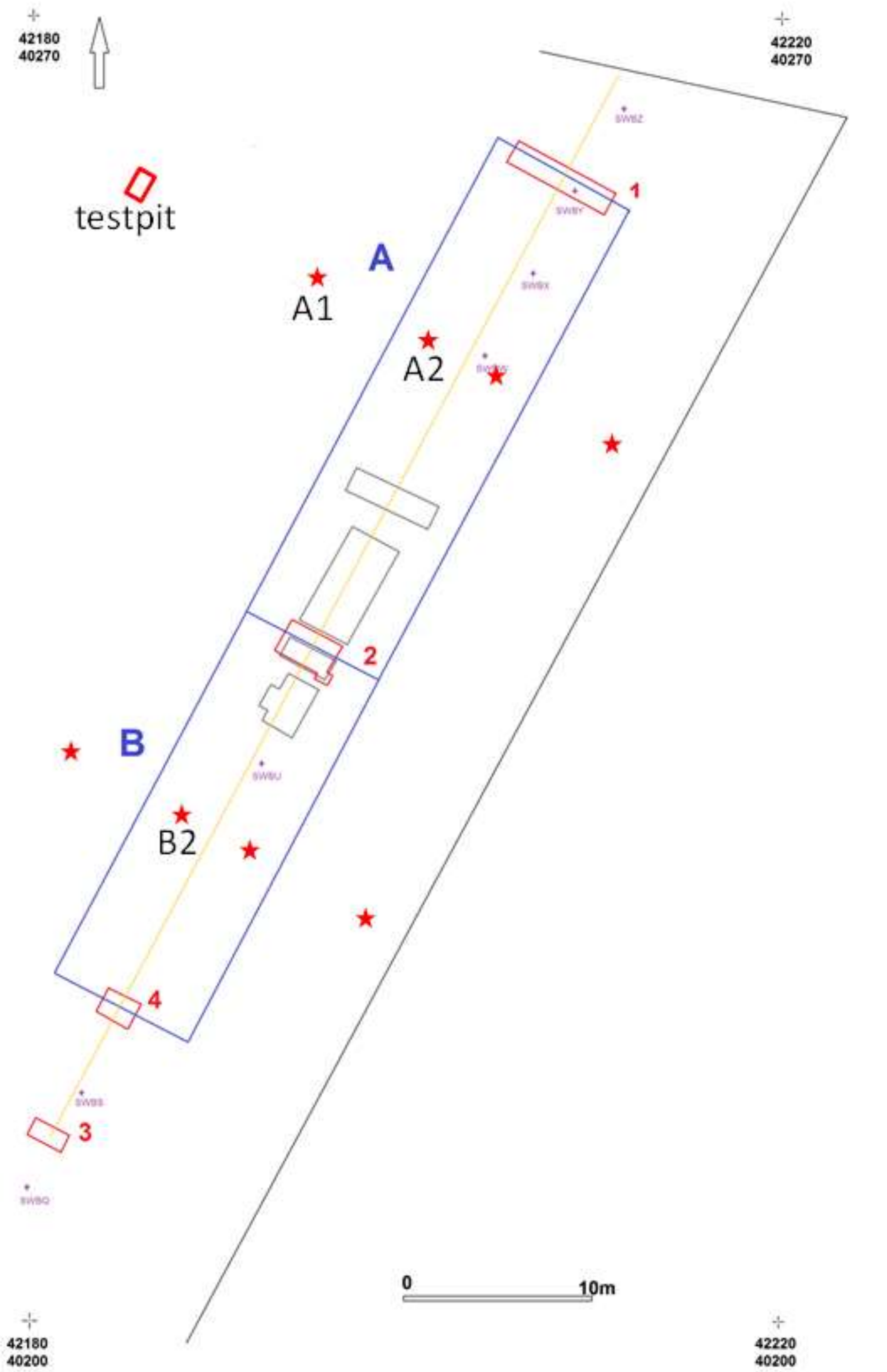


Figure 31. Map of site with location of monitoring equipment and test pit. Blue line: location of plastic membrane. Red stars: approximate location of dipwells. Oxygen, temperature and water content sensors were installed within 1 m of dipwells A1, A2 and B2.

Location	Depth below ground surface (cm)	Oxygen sensor number	Temperature sensor number	Water content sensor (not numbered)
A1	50	1	1	X
A1	100	2	2	X
A1	150	3	3	X
A2	50	4	4	X
A2	100	5	5	X
A2	150	6	6	X
B2	50	7	7	X
B2	100	8	8	X
B2	150	9	9	X

Table 8: Installation depth of oxygen, temperature and water content sensors

Optical oxygen sensors (dipping probe DP-PSt3 from PreSens) were installed from the ground surface through a custom made removable installation tube (Ø= 1½ cm) that causes only minimal disturbance to the peat (Figure 31). Installation depth and sensor numbers are described in Table 8. Temperature sensors (Pt100 from PreSens) were installed next to the oxygen sensors to allow temperature compensation of the oxygen readings. The connectors for the oxygen and temperature sensors were placed in Peli-cases (water tight IP67). All cables were passed through a single cable gland, and it was attempted to keep the cases watertight by filling the gland with silicone sealant. Readings of the oxygen concentrations are carried out with a Fibox4 instrument from PreSens during site visits. Some of the Pt100 temperature sensors have stopped working, so a manual temperature compensation of the oxygen readings has been carried out afterwards using the software PreSens Oxygen Calculator and temperature measurements from the SM300 sensors (below).

SM300 water content sensors from Delta T instruments were installed at 50, 100 and 1.50 cm depth below the ground surface at A1, A2 and B2. For the sensors at 50 cm depth, a small hole was dug down to the plastic membrane (at 45 cm depth), it was slit open, the sensor was installed just underneath the membrane, and the slit closed and covered with another piece of membrane, to try to stop the vertical migration of water through the profile at this point. For the sensors at 100 and 150 cm depth a mechanical corer made a hole of ca 5 cm diameter, and the SM300 sensor was carefully pressed down using a removable extension shaft. The hole was subsequently closed with peat from the corer.

The SM300 sensors were connected to three GP2 data loggers from Delta-T, using the wiring shown in Appendix 1. The GP2 loggers and flight cases were placed in plastic boxes as an additional protection, even if the boxes are not completely water tight. The loggers were programmed to measure the water content and temperature every 6 hours. Initially, the standard calibration for organic soil was used, however, the water contents at the site turned out to be beyond the normal measuring range of the sensors, so it was necessary to make a site specific calibration in the laboratory and to re-program the loggers. Reprogramming took place in May 2017, and all the data presented here have been re-calculated according to the new calibration. One of the SM300 sensors (A1, 50 cm depth) was replaced on the 19th of July 2018.

A small test pit was dug 25-30 m from the trackway to obtain peat samples for laboratory measurements and to determine profiles of in situ water content and pH. The pit was dug to 160 cm depth, corresponding to the depth of the trackway. Ring samples of peat for porosity measurements were taken at 25 cm intervals using 100 cm^3 soil rings. Bulk samples for measuring the reactivity of the peat were taken at the same depths. A WET probe from Delta T was used to measure water content and conductivity at 10 cm intervals in the test pit. A solid state pH probe (SS37 from Hach) was used to measure the in situ pH at 20 cm intervals. Further ring samples for porosity measurements were taken at A1, A2 and B2 using a hand corer, where peat from the corer was used to fill the 100 cm^3 soil rings. This is not the ideal way to take ring samples, but the results may be used to check for local variations and validate results from the test pit.

The ring samples were analysed back in the laboratory, measuring the water content (drying at 105 °C) and loss on ignition (after ignition at 450 °C). The loss on ignition is interpreted as the organic content. The porosity is calculated as described in Matthiesen et al. (2015) and in Appendix 2.

Bulk samples have been used for measurement of peat reactivity under controlled conditions in the laboratory. The reactivity is measured as the oxygen consumption of the samples at four different temperatures (1, 5, 10 and 15 °C) and at in situ water content as described in (Hollesen and Matthiesen 2015).

Daily precipitation for the area (South West England and Wales) has been found at https://www.metoffice.gov.uk/hadobs/hadukp/data/daily/HadSWEP_daily_qc.txt. Maps on https://www.metoffice.gov.uk/climate/uk/summaries/anomacts show how wet/dry the conditions have been in the monitoring period, compared to the 1981-2010 average values. Table 9 gives a summary of the data, showing that 2017 had a relatively dry winter, spring, and autumn and a relatively wet summer, 2018 had a wet spring and a dry summer, while 2019 had a dry winter and wet summer. The summer and early autumn period is considered the most critical in terms of preservation conditions, and by now the monitoring period covers both a very dry (2018) and two wet (2017 and 2019) summers.

		mm rain	% of avg 1981-2010
2017	Winter	238.5	63
	Spring	215.6	85
	Summer	304.5	125
	Autumn	322.7	84
2018	Winter	390.6	103
	Spring	321.3	126
	Summer	154.1	63
	Autumn	384.2	100
2019	Winter	335.4	89
	Spring	254.9	100
	Summer	285.2	117

Table 9: Precipitation data for South West England and Wales, from https://www.metoffice.gov.uk/climate/uk/summaries

The two monitoring transects, each consisting of four standpipes, were installed between the 28th and 30th March 2017. Boreholes were drilled to a maximum depth of 2.0 m below ground surface using a lightweight windowless dynamic rig (provided by GASite Investigations Ltd). Slotted plastic tubes, of diameter 60mm and 1.0 m long were inserted into each borehole to give a response zone of between 2.0 and 1.0 m below ground surface. Fine gravel was used as a filter and the upper section of each borehole was sealed with bentonite clay pellets to prevent downward movement of surface water into the pipe. Where the standpipes lay directly above the alignment of the timbers, the pipes were inserted to a depth of circa 1.6m to avoid penetrating the trackway.

Figure 32: Lightweight dynamic drilling rig on site drilling transect B, left, and right: the 1.0m section of slotted pipe before installation

Water levels are logged using the Rugged TROLL™ 100 pressure transducer (from In-Situ Europe) suspended below the groundwater table in each standpipe. As these transducers are of the non-vented type, a BaroTROLL™ (recording barometric pressure) was deployed to enable compensation for localised changes in atmospheric pressures. This was installed in A1, ensuring that it remained dry and continually above the groundwater table throughout the monitoring period.

Figure 33: The Rugged TROLL™ 100 transducer.

Prior to installation each transducer was programmed to record at 6 hourly intervals, commencing 30 minutes following insertion into the standpipes, and data download was carried out periodically by Richard Brunning.

Oxygen, water and temperature results

Henning Matthiesen

Results from the laboratory analysis and the field measurements during installation of equipment are presented and briefly discussed in Appendix 2, while this section focuses on the results from data loggers and from subsequent field visits. Monitoring of water content and temperature has been ongoing since 30th March 2017, and the latest data were downloaded on the 30th of September 2019. Measurements take place every 6 hours, from which mean daily values are calculated. Oxygen concentrations were measured by Richard Brunning at 23 site visits at 1-4 weeks intervals during the first two years, and at 2 visits during 2019. Figure 34 presents a first overview of all the data, while the different parameters are presented in more detail in figures 35-37:

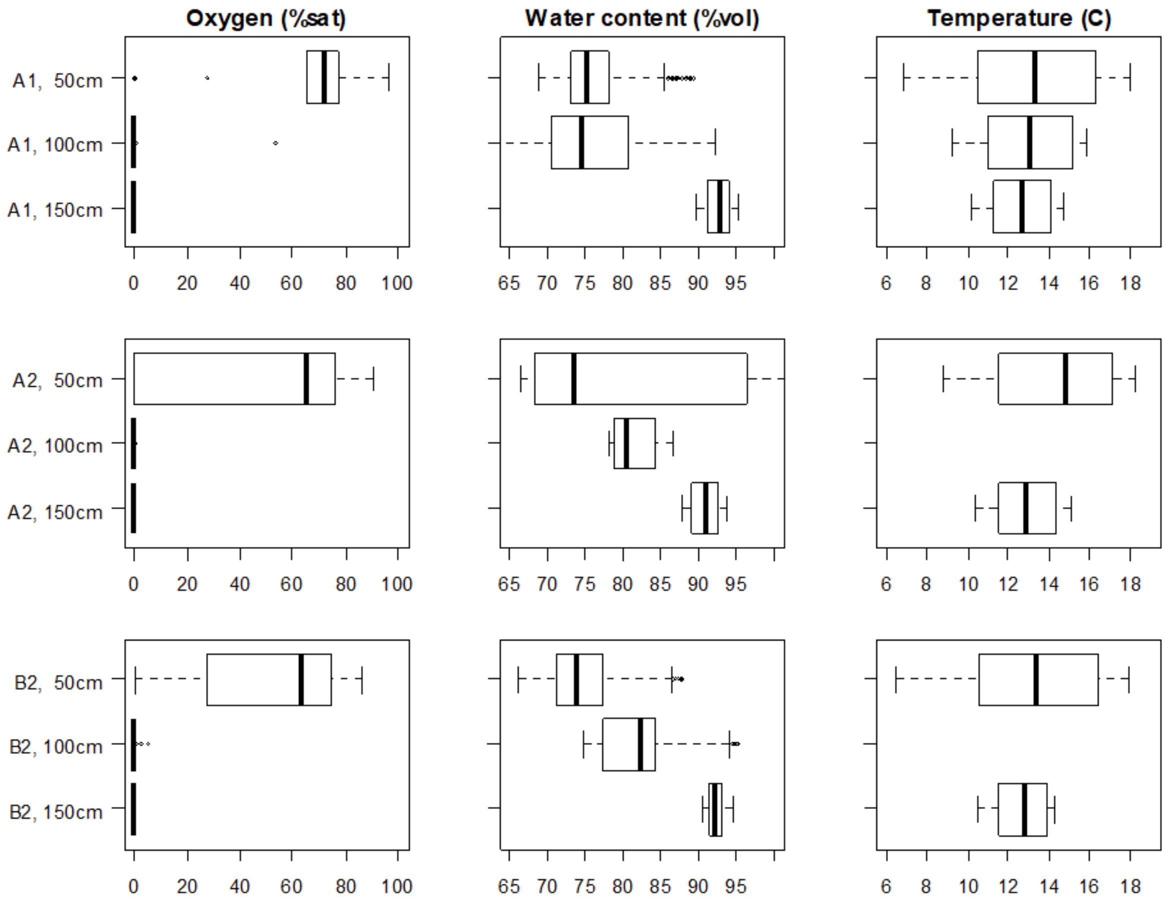


Figure 34: Boxplots giving a first overview of the distribution of the monitoring data. For each sensor the thick line in the middle shows the median of all measurements, the box shows the interval including 50% of all measurements, while the whiskers and dots show the extreme values (maximum and minimum). The number of measurements are 25 for the oxygen sensors and up to 915 (mean daily values) for the water content and temperature. Lacunas in some of the data series reduce the number of measurements as described below, and results from two of the temperature sensors are not shown due to bias or too few measurements.

The boxplots indicate that oxygen is almost exclusively found at the 50 cm sensors, that the water content generally increases with depth, and that the yearly temperature fluctuation decreases with depth. Furthermore, the box plots give an indication of how the different data are distributed. Note that the data represents three summers but only two winters, and that the median values in the plots will differ from the yearly median.

Water level
Data series for the ground water level measured in dipwells at A1, A2 and B2 are shown in Figure 34.

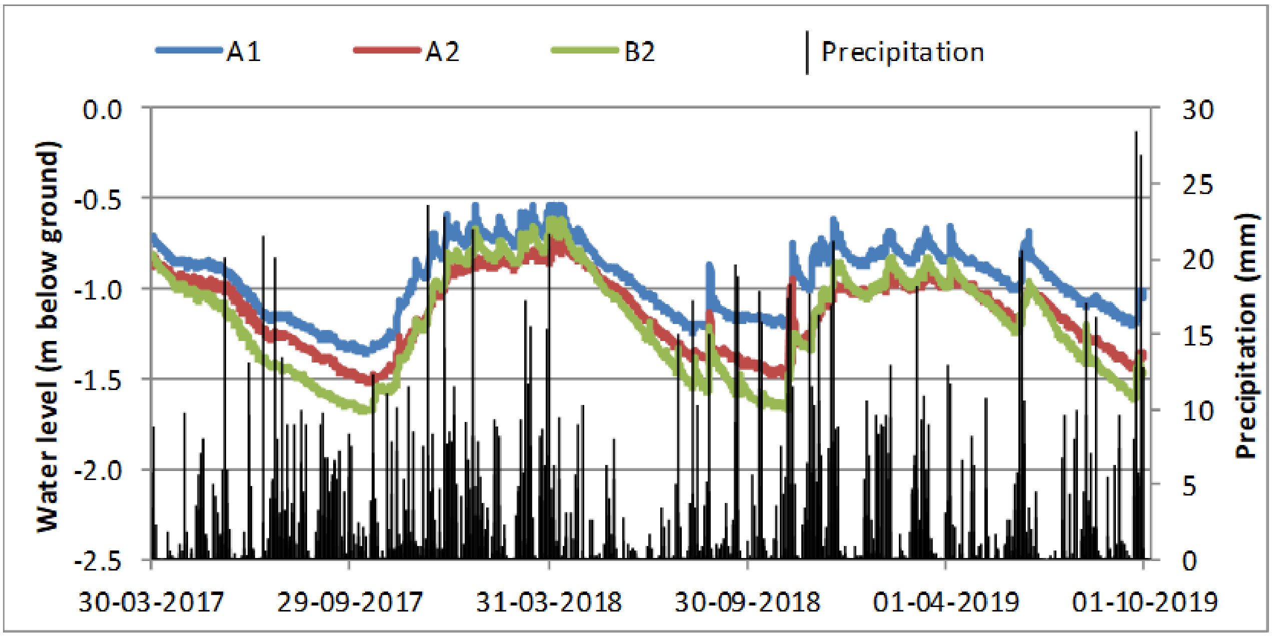


Figure 34: Ground water level measured in dipwells at A1, A2 and B2; the conversion to m below ground is based on manual measurements on the 30/3/2017

The results will be discussed in detail by Ian Panter (below) and are only presented here to enhance the discussion on other parameters. Regarding the quality of the data it is noted that:

- the recalculation to “m below ground” is based on a single manual measurement at the installation of the equipment (30/3/2017), and it is recommended to make a renewed manual measurement to check for possible drift

Oxygen
Time series for the oxygen measurements are presented in figure 35. The results are given as “% saturation”, where 0% indicates anoxic conditions, and 100% indicate the concentration in atmospheric air or water in equilibrium with atmospheric air.

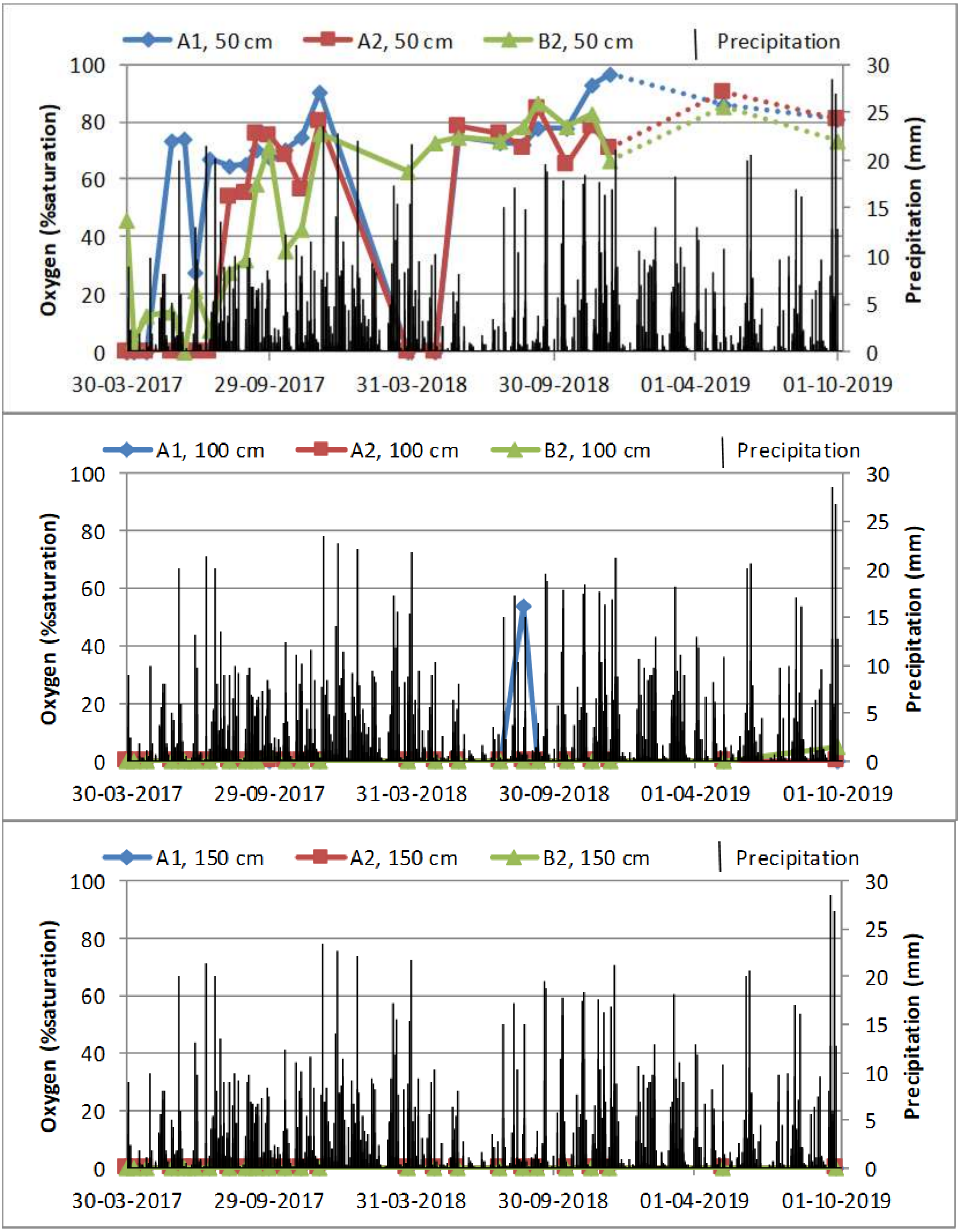


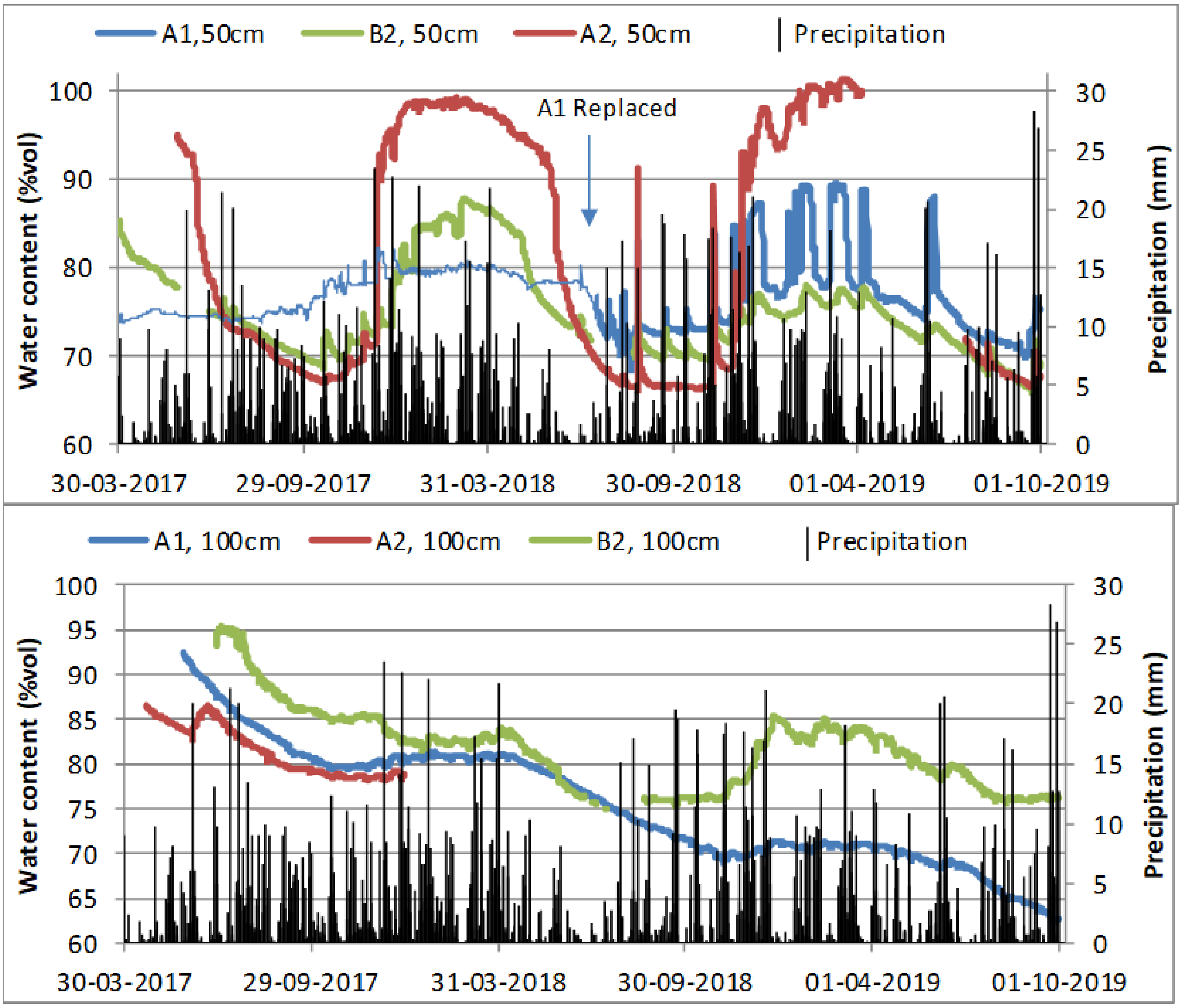
Figure 35: Time series for oxygen measurements at 50, 100 and 150 cm depth at the 3 locations. For comparison the daily precipitation is also shown.

The results are discussed in detail below, but regarding the quality of the data it is noted that:

- Measurements at 1-4 weeks interval (or 5 month interval in 2019) will not reveal the full variations in oxygen concentrations, as these can be extremely dynamic and may change within a few hours (Matthiesen et al. 2015)
- Initial results from the 30-03-17 may be biased, as the readings were taken right after the installation of the sensors.

Water content

Time series for the water content are shown in figure 36.



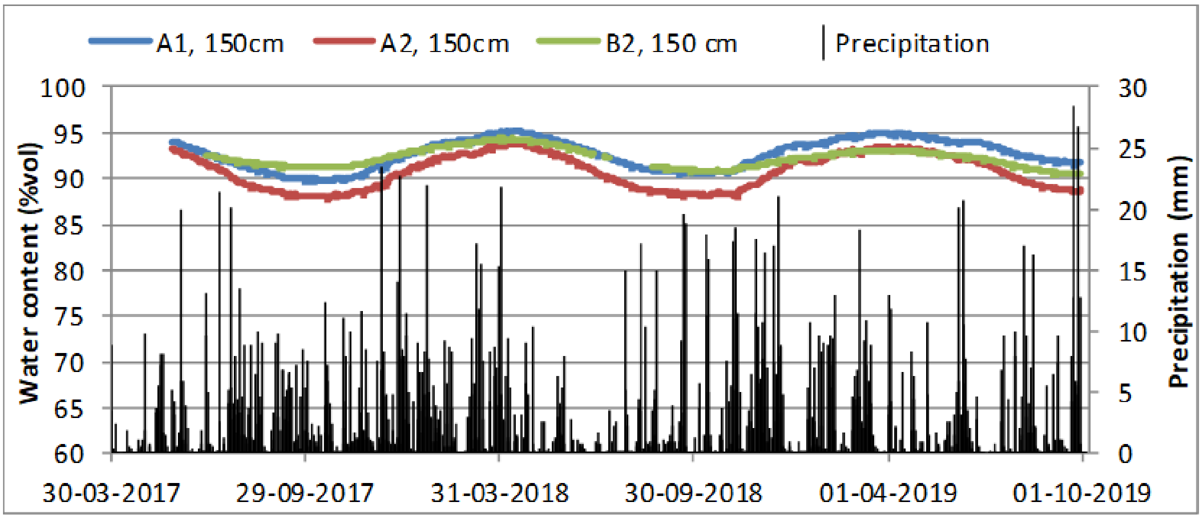


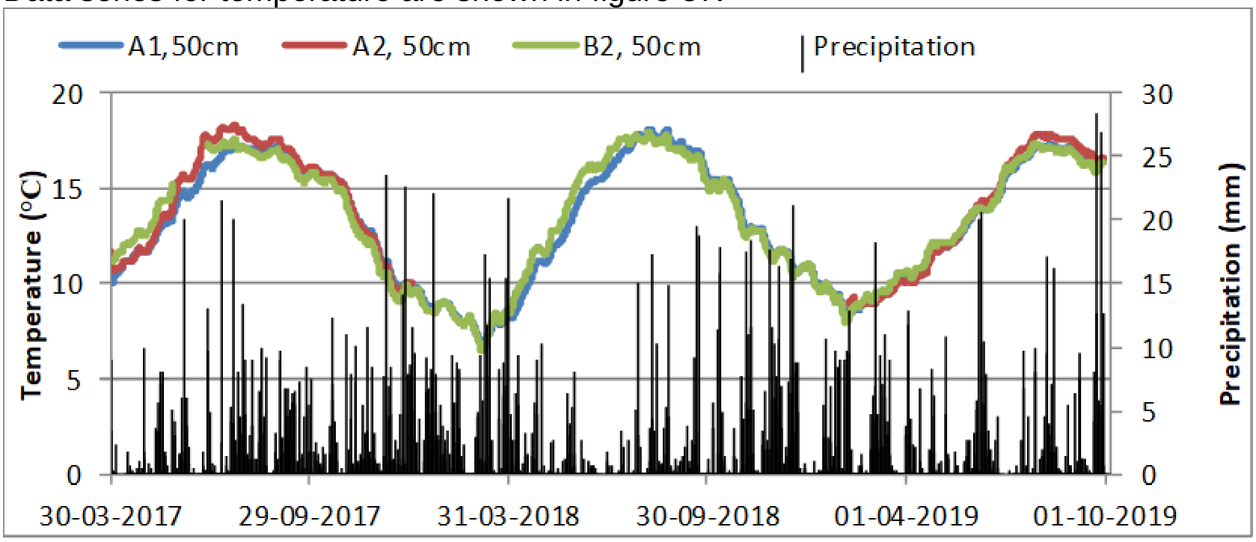
Figure 36: Time series for water content measurements at 50, 100 and 150 cm depth at the 3 locations.

The results are discussed in detail below but regarding the quality of data it is noted that:

- The water contents are generally high and beyond the normal calibration range of the sensors, so a site specific calibration has been made. The accuracy of the measurements is reduced for water contents above 50% vol according to the manufacturer Delta-T
- The 50 cm sensor at A1 initially gave unrealistic low fluctuations and was replaced on the 19th July 2018; results from the previous sensor have been discarded in the data analysis below.
- Two other sensors (A2, 50 and 100 cm) have shown permanent or temporary problems
- Initial results from the first months may be biased due to disturbance of the peat layers

Temperature

Data series for temperature are shown in figure 37.



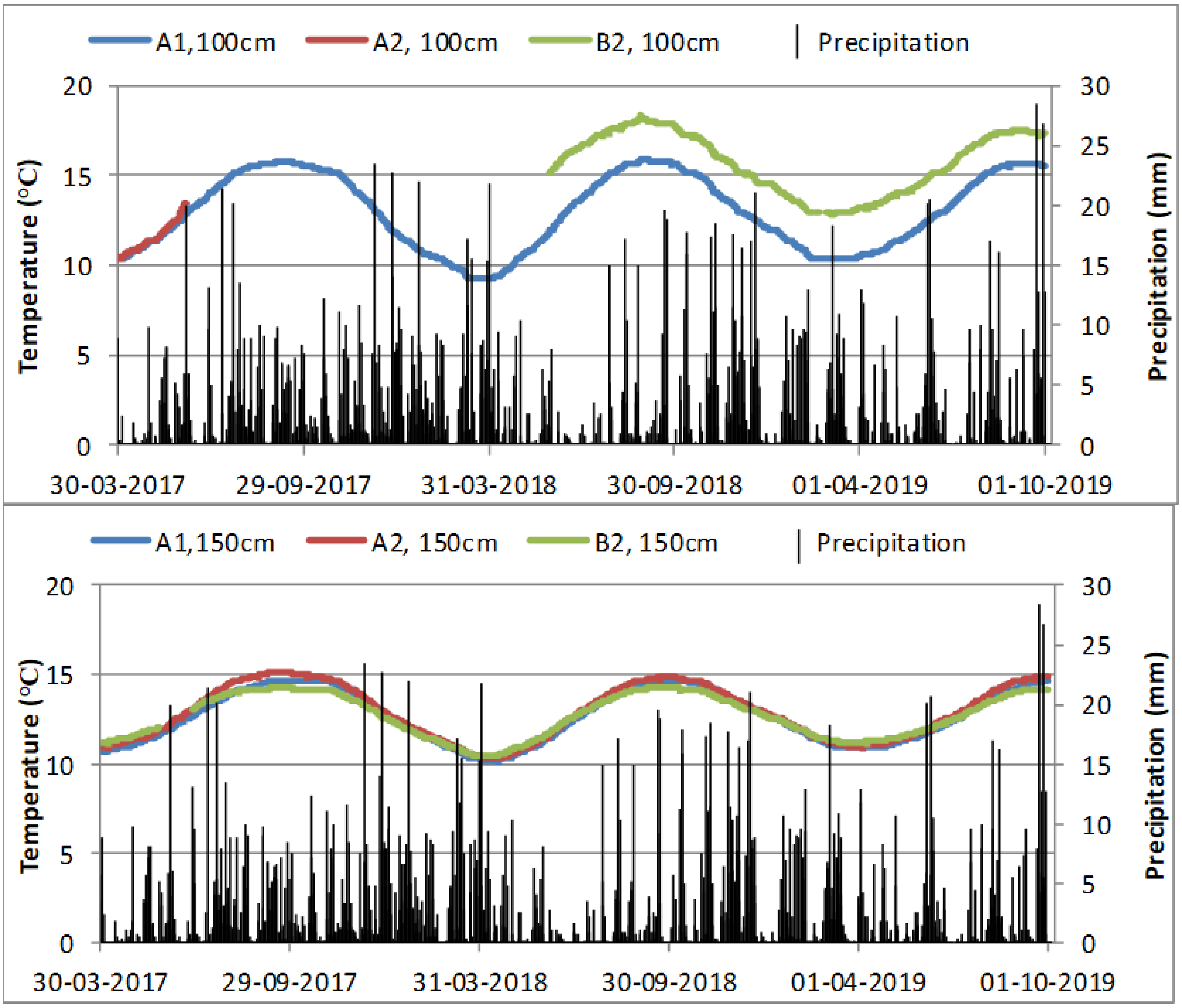


Figure 37: Time series for temperature measurements at 50, 100 and 150 cm depth at the 3 locations

The results are discussed below but regarding the quality of data it is noted that:

- The results for the 3 monitoring locations are very similar and the data quality is considered good, except the 100 cm sensor at B2 which seems to have a bias of approx. 2 ℃.
- Three out of nine temperature sensors have shown problems or stopped working; it should be checked if this is due to the SM300 sensors themselves, or due to the datalogger or cabling used (see appendix 1).

Discussion

The discussion focuses on the following three questions:

- what are the preservation conditions for the Sweet Track timbers in this area?
- can we document an effect from the membrane?
- what is the correlation between precipitation, water content, temperature and oxygen?

Preservation conditions for the Sweet Track timbers in this area

The Sweet Track timbers are found approximately 160 cm below the ground surface in this area. The preservation conditions are considered good at this depth (details below), but it is relevant also to look at the conditions above the timbers:
At 50 cm depth, relatively high oxygen concentrations are measured at all site visits during summer and autumn for all stations, and at B2 high oxygen concentrations are even found in the spring 2018. The groundwater level is permanently below 50 cm depth at all three locations. The water content sensors at 50 cm show a gradual drying out over the summer, but also some examples of a fast response to precipitation. The temperature varies between 7 and 18 °C during the monitoring period with maximum temperatures in July/August, and with some short term fluctuations. The fluctuations may be due to variations in air temperature, but there also seems to be some correlation to the precipitation, which may reflect that rainwater infiltrating into the peat reaches the temperature sensors at 50 cm depth relatively fast. Overall, as expected the conditions at 50 cm depth are more dynamic than in the deeper deposits.

At 100 cm depth oxygen has only been observed at three site visits: at B2 in September 2017 at a low concentration (2.5 % saturation), at A1 in late August 2018 at a more substantial concentration (54 % saturation), and at B2 in late September 2019 (5% saturation). The groundwater level is below 100 cm depth from approximately June to December each year. Water contents are less dynamic than at 50 cm depth, but show a gradual decrease over the summer and autumn 2017, a constant content during the winter, and a continued decrease over the dry summer in 2018 (for A1 and B2 – A2 stopped measuring). Recharging of the layers starts around December 2018 at B2, while no recharge is observed at A1 which is surprising as the groundwater level measurements indicate that the 100 cm sensors are flooded from approximately December to June. The temperature varies between 9 and 16 °C with maximum temperatures in September.

At 150 cm depth no oxygen has been measured during site visits. The water content sensors show slightly decreasing values over the summer reaching minimum levels in September to October, but this is not necessarily due to drying of the soil: the lowest groundwater levels during the monitoring period were approx. 1.34 m below ground-level for A1, 1.51 m for A2 and 1.67 m for B2, and these low levels were only measured for short periods (figure 34 and Panter below). Thus, at A1 the water level never reaches the sensor at 150 cm below ground-level, but still a slight decrease in water content is observed, which it may be due to a temperature effect on the measurement, or due to anaerobic gases (methane/CO_2) accumulating in the deeper peat layers replacing some of the water. The temperature measurements show a modest variation between 10 and 15 °C during the monitoring period with maximum temperatures reached in September/October.

With regard to the preservation conditions around the Sweet Track timbers at 160 cm depth it is unlikely that any oxygen has reached them during the monitoring period from 2017 to 2019. Direct measurements of oxygen are only carried out at intervals, but none of the measurements showed oxygen at 150 cm depth, the water content measurements in the deeper deposits didn’t indicate any abrupt changes in between the site visits, and the groundwater level was almost permanently above the timbers during the monitoring period (figure 34). Thus, the 160 cm peat above the timbers seems to be a sufficient buffer zone to ensure anoxic conditions at the timbers, at least in 2017-2019.

Regarding the stability of this buffer zone, some organic decomposition will take place in layers where oxygen is present, and the future thickness of the buffer zone depends on the balance between decomposition and accumulation of new organic matter. The decomposition may be estimated by a desk top calculation: Based on Figure 35 it is estimated that there are oxic conditions at 50 cm depth for at least 200 days per year, mainly during summer and autumn. The average peat temperature is around 15 °C in this period (Figure 37), and laboratory measurements showed that the oxygen consumption at this temperature is close to 0.1 mg O_2/g dw/day (dw: dry weight) for peat at 50 cm depth (Figure A2). 200 days with oxic conditions gives an oxygen consumption of 20 mg O_2 /g dw/year, which equals 22 mg O_2/g org.mat/year, as 90% of the dry weight is organic material (Table A1). If a very simple stoichiometry is assumed, where the oxygen is used to oxidize organic matter to CO_2 ($CH_2O + O_2 \rightarrow CO_2 + H_2O$), this corresponds to 21 mg organic material, or approx. 2% of the organic material, being oxidized per year at 50 cm depth. This degradation may lead to subsidence of the ground surface over time, and the estimate may serve to illustrate the magnitude of the ongoing processes. However, there will also be an accumulation of new organic material from plants and roots in the upper soil layers. This has not been included in the current estimate, but it may help explain the higher reactivity observed in layers above 50 cm (Figure A2) as fresh material is typically more reactive. More detailed calculations are described in Hollesen et al. (2016) which may also be applied to the Sweet Track data.

Effects from the membrane

The possible effects of the membrane are of prime interest, can be evaluated by comparing the monitoring results from the reference location A1 with the two locations A2 and B2 underneath the membrane.

Looking at the oxygen data first, figure 35 shows a tendency to lower oxygen concentrations at A2 and B2 during the spring months 2017 when compared to A1 (at 50 cm depth). In other words, it seems that the membrane can delay the appearance of oxygen at 50 cm depth. However, this difference is not observed in 2018 or 2019, and if we look at the all measured oxygen concentrations over the whole period (25 site visits), there is no significant difference (paired two-sided t-test comparing A1 with A2 and B2 gives p-values of 0.20 and 0.38, respectively, where p-values <0.05 are normally used to describe the differences as significant). Looking at the deeper deposits, a high concentration of oxygen was observed at 100 cm depth at A1 outside the membrane in August 2018 while there were anoxic conditions at A2 and B2. This could be an effect of the membrane, but a single measurement is too little to make any firm conclusions. Two other occurrences of oxygen at 100 cm depth were observed in September 2017 and 2019, both at B2, while there were anoxic conditions at A1 and A2.

As for the water content measurements, the water content sensor at 50 cm depth at A1 was replaced in July 2018, and the results from the previous sensor have been disregarded. After July 2018 the water content during summer has been slightly higher at A1 compared to A2 and B2 at 50 cm depth, while the winter water content was highest at A2, but the absolute numbers should be interpreted with some caution due to a reduced sensor accuracy for water contents over 50% vol. Looking at the deeper deposits at 100 cm depth, the water content has generally been higher at B2 compared to A1, while the sensor at A2 has stopped working. It is noted in particular that the water content at B2 starts increasing in December after the dry summer in 2018, while A1 shows a stable low level over the winter and then a continued decrease over the summer 2019. The low water content at the A1 sensor is surprising as Figure 4 indicates that there should be saturated conditions at 100 cm depth from December to June, and it cannot be excluded that the results are biased for instance by drift or gas trapped around the sensor. It is thus uncertain, if the current higher water content at B2 compared to A1 is real and if it is an effect from the membrane. At 150 cm depth the water contents are very similar at the 3 locations. Overall, there are no certain indicators of positive effects from the membrane on the peat moisture.

As for the measured ground water levels (figure 34) the data show that the water level is up to 50 cm higher at the reference site A1 compared to under the membrane, which would indicate that the membrane has a negative effect on the groundwater level and preservation conditions. However, it is recommended to make a renewed manual measurement at the site to compensate for possible drift, and also to calculate the absolute heights (in meters above sea level) of the groundwater level to evaluate the flow direction.

As for the temperature measurements, there is no evidence that the membrane has affected the peat temperature.

Overall, the monitoring data shows no clear effect from the membrane on the preservation conditions.

Correlations between precipitation, water content, temperature and oxygen
The correlation between water content and oxygen have been evaluated in detail for monitoring data from the Bryggen site, where both parameters have been monitored continuously for several years in different types of urban deposits (Matthiesen et al. 2016; Matthiesen et al. 2015). In the Bryggen deposits, oxygen typically occurs when the air content of the soil exceeds 10-15% vol (Matthiesen et al. 2015) and it is interesting to see if this preliminary rule of thumb also applies to the more organic peat deposits found at the Sweet Track. Figure 8 shows the correlation between water content and oxygen concentration measured during site visits. The data from A1, 50 cm depth, only includes measurements after replacement of the water content sensor.

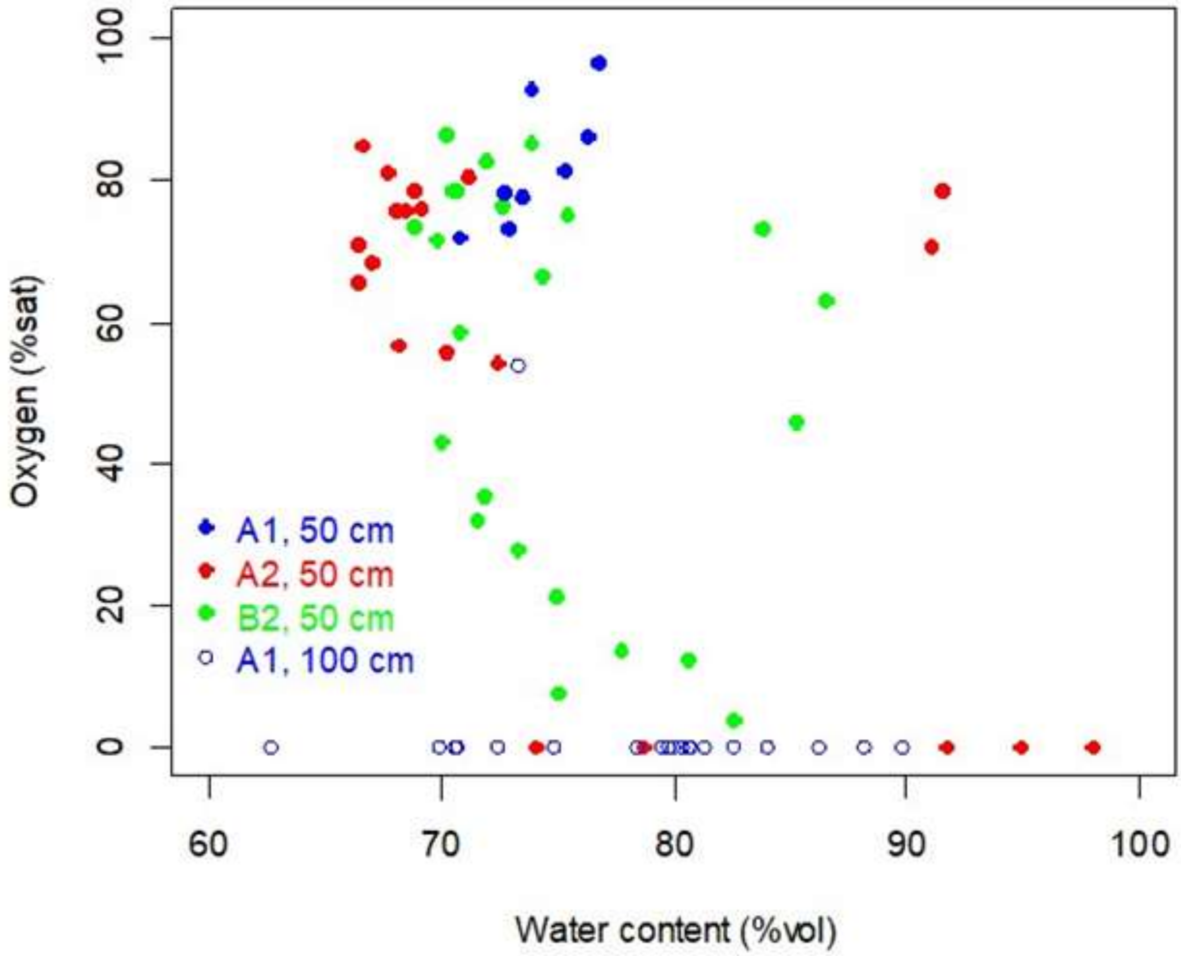


Figure 38: Correlation between oxygen concentrations and water content for all sensors with occasional oxygen presence

Figure 38 indicates that in general the oxygen starts appearing when the water content is below approximately 80% vol, so this can be used as a first estimate of the "critical water content" in these deposits. Five points do not follow this general rule and are discussed below. The porosity of the peat layers is 90-95% vol (Table A1), so a water content of 80% vol corresponds to an air volume between 10 and 15% vol. This is in good correspondence with the Bryggen data, even if it must be emphasized that the air content can only be a rough proxy for the presence of oxygen. The air content has a strong influence on the oxygen supply through diffusion (Jin and Jury 1996), but the actual oxygen concentration in the deposits will also depend on both the supply path and on the oxygen consumption, which again depends on the temperature and soil reactivity. Regarding the five points in the circle, four of them are from the cold winter period where oxygen consumption is slower (cf. Figure A2) which may explain why the oxygen can reach a depth of 50 cm before being consumed.

Summary

Summing up it is noted that:

- oxygen has been measured at 25 site visits during 2017, 2018 and 2019, showing anoxic conditions at 100 and 150 cm depth at all three locations at all visits (except three)

- it is estimated, that no oxygen has reached the Sweet Track timbers at 160 cm depth during the monitoring period, and that the preservation conditions for the timbers are good
- there are no clear effects of the membrane on the preservation conditions: the groundwater level measurements indicate a negative effect that should be confirmed through manual measurements, the peat moisture measurements indicate a negative (50 cm), uncertain (100 cm), and no (150 cm) effect, and finally the oxygen measurements show no significant effects (positive or negative) at the same depths
- there is a distinct correlation between the presence of oxygen and the water content of the peat, confirming earlier observations from urban deposits

Additionally, it is noted that:

- for the upper deposits, oxic conditions have been found at 50 cm depth at all three locations for most site visits
- it is estimated that in these oxic deposits approximately 2% of the organic material may degrade within a year, based on the environmental monitoring data in combination with controlled degradation experiments in the laboratory

Groundwater monitoring results

Ian Panter

Each dataset has been calibrated with two programmes – first using the "Win Situ Baro Merge™" programme to compensate for localised variations in barometric pressure, using data recorded by the BaroTroll installed in A1. The readings were then converted to depth to groundwater (in metres, from the ground surface) using the Post Level Correction™ programme, based on the initial depth of the groundwater in each standpipe measured with an audible dipmeter on the 30th March 2017 (from the top of the standpipe) and further corrected based on manual readings taken by Richard Brunning on 3rd January 2020. Finally, the depth readings were corrected to m OD.

Groundwater trends for both transects are illustrated in Figures 39 (Transect A) and 40 (Transect B) along with monthly rainfall data for South West England and South Wales provided by the Met Office.
https://www.metoffice.gov.uk/pub/data/weather/uk/climate/datasets/Rainfall/date/England_SW_and_S_Wales.txt

The upper level of the Sweet Track, at circa 1.87m OD is also shown on each plot. Overall, both transects exhibit very similar trends throughout the monitoring period, reflecting the influence of precipitation on recharge of the peat. Groundwater levels tend to fall in the late spring and summer/early autumn, when evapotranspiration rates will be at their greatest, then rising again as effective rainfall increases during late autumn and winter. For the duration of the monitoring period, each successive year has been slightly wetter than the preceding year: 1185mm total in 2017, 1245mm for 2018 and 1390mm for 2019. The summer of 2018 was the driest during this period though at 157mm, whereas the summer in 2017 was the wettest at 304mm which was more rain than in the winter and preceding spring. The autumn of

2019 was the wettest throughout the period, with total rainfall of 537mm, almost as much as the autumns of 2017 and 2018 combined.
Despite these variations in seasonal rainfall patterns, the hydrological cycle continued throughout the period, and therefore, as groundwater levels continued to fall during the spring and summer there is no evidence to indicate that the geotextile wrapping was effective at retaining water around the timbers of the Sweet Track.

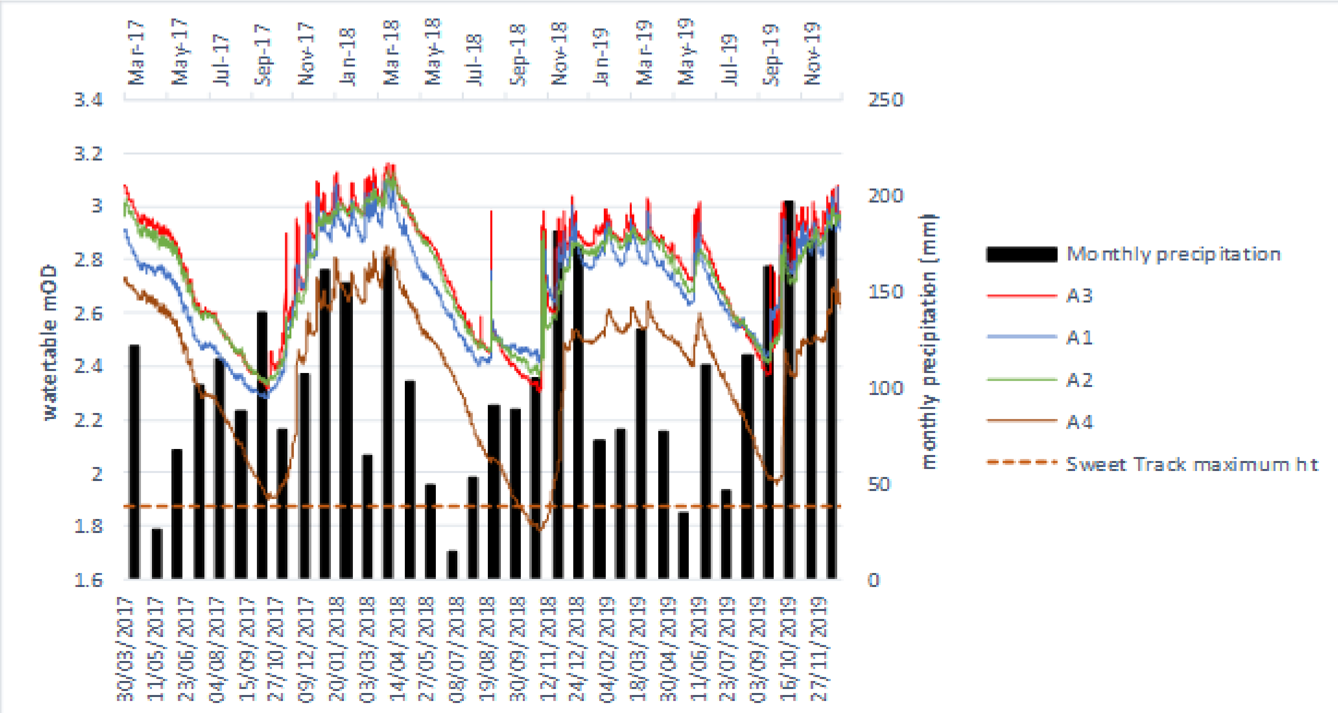


Figure 39. Transect A: groundwater levels between 30/03/2017 and 31/12/2019

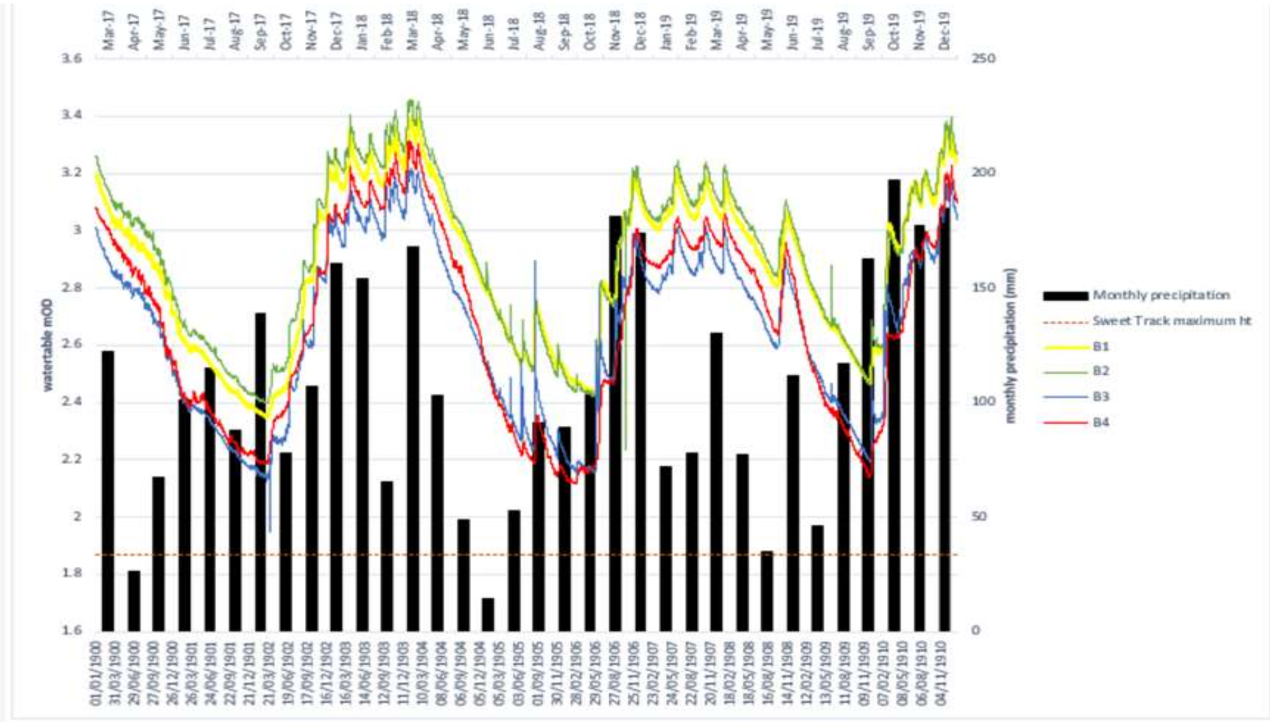


Figure 40. Transect B groundwater levels between 30/03/2017 and 31/12/2019

Figure 41 below illustrates the groundwater trend for the four standpipes located within the wrapped zones and directly above the timbers (A2, A3, and B2, B3). Again, there is little or no difference between transect A and B and therefore it can be concluded that neither wrapping technique under investigation proved capable of influencing groundwater dynamics and retaining water at a higher level above the Sweet Track.

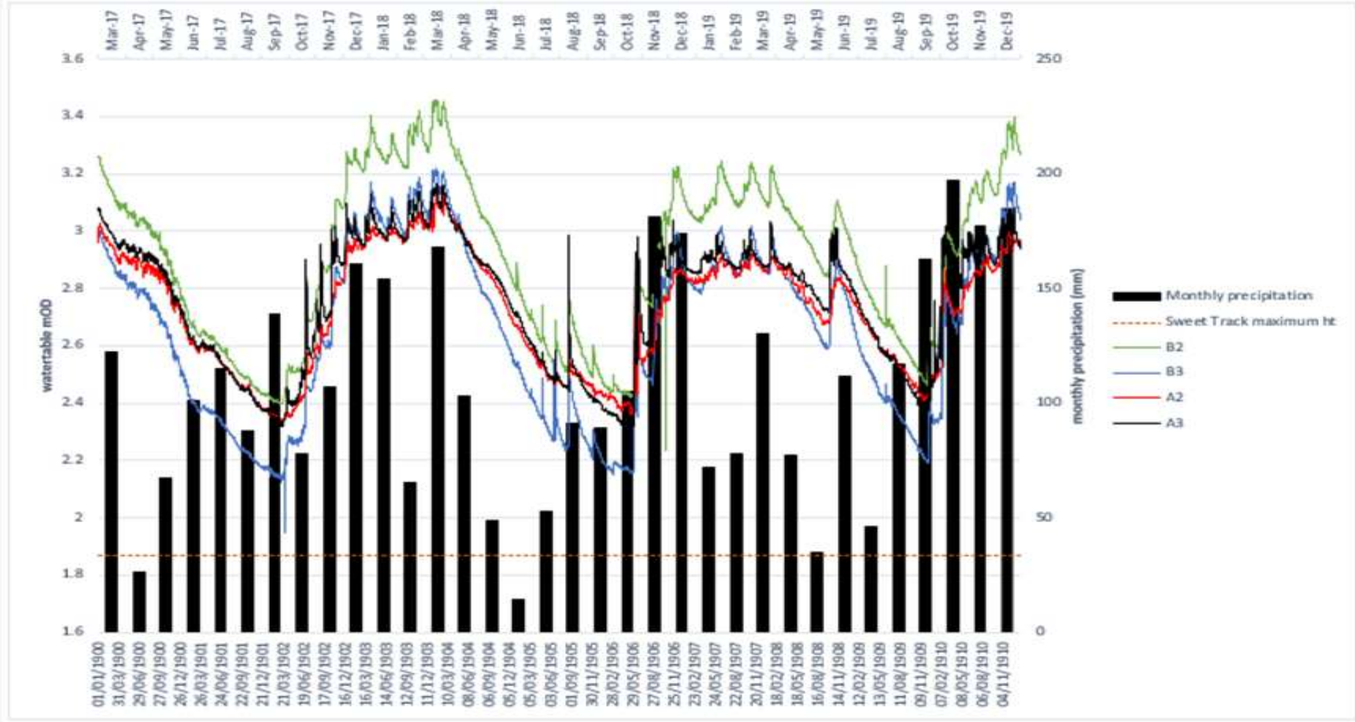


Figure 41. Groundwater levels in A2, A3, B2 and B3, within the wrapped zones.

Despite this though at no time between 2017 and 2019 were timbers exposed above the water table and it must be assumed that saturated conditions have been maintained around the timbers throughout.

The lowest groundwater levels were recorded in standpipe A4 (1.78m OD) which is closest to the tree line to the east of the track. The roots of these trees will be creating a drawdown effect coupled with increased evapotranspiration when in leaf. Such conditions, whilst not directly lowering the groundwater sufficient to expose the wood, will create the potential for a horizontal water gradient groundwater flow thereby preventing the establishment of stagnant conditions necessary for continued preservation of the timbers. However, the work carried out by Henning Matthiesen (Matthiesen, 2020) has demonstrated that anoxic conditions existed at 1.87m OD (Matthiesien's sensor at 160 cm below ground surface) throughout the monitoring period, although oxygen was recorded on three occasions at the probe located at circa 2.47m OD (100cm below ground surface).

Summary

Two sections of the Sweet Track were "wrapped" in a geotextile membrane, and a groundwater monitoring program was designed to assess whether such membranes were effective at retaining groundwater during periods of low rainfall and high evapotranspiration rates.

The duration of the program has been sufficient to determine that neither wrapping methodology deployed across this section of the Sweet Track had any influence on the usual hydrological cycle where water levels fall during the summer season and rise during the autumn and winter months. Water levels were not retained even during the wetter summers of 2017 and 2019, indicating that evapotranspiration remains one of the critical drivers of lowering groundwater levels in this landscape.

However, throughout the period the watertable never dropped below the uppermost level of the timbers, which have remained saturated and in anoxic conditions, which are favourable to the continued in situ preservation of the Sweet Track.

7. CONCLUSION

The fieldwork confirmed the location and depth of the Sweet Track and the exact position of the previous Somerset Levels Project trenches. The trackway structure was only encountered in Trench 1. In Trench 2 it had been previously been excavated by the Somerset Levels Project. Trench 3 was positioned so close to the edge of Shapwick island that it is unlikely that a wooden structure would have been required in that location, if indeed the peat deposits in that area date back as far as the early Neolithic.

In Trench 4 a layer containing charcoal and worked wood may represent a continuation of the line of the Sweet Track, although it could represent later activity. The Somerset Levels Project trenches at SWB, a few metres further from the island, showed that the trackway line was represented by a varied combination of charcoal, clay and worked wood. The character of the material in Trench 4, and its OD height, would be consistent with a continuation of that fragmented form of the structure as it neared Shapwick Burtle island.

The character of the trackway in trench 1 resembles the typical form of the trackway as it was seen in site SWC, a short distance to the north. The low angles of the paired hazel stakes, which formed the cradle for the walkway planks, suggests that the water levels were quite shallow at that point, near the edge of the wetland. The dominance of ash in the wood assemblage is unusual, and the woodchip and woodworking waste suggests that large ash timbers were being processed, while finer working of oak timbers was taking place, possibly because they had been fully shaped elsewhere. The large quantities of woodworking waste of different species suggest that the Trench 1 area was a location where a lot of woodworking was taking place, before the finished timbers were taken further out into the deeper wetland to form the trackway.

The wooden material in Trench 1 exhibited some well-preserved toolmarks, and it proved possible to establish species identification for almost all the samples examined. However, many of the wooden items were in an obviously very advanced state of decay. The poor condition of the material from all the trenches was confirmed by the detailed analysis (Appendix A) carried out by the Mary Rose Trust. This suggests that the trackway would be highly vulnerable to desiccation.

The poor condition of the trackway structure in Trench 1 may be a product of decay that occurred in the Neolithic period, especially if the trackway structure in that location was situated in a shallow water zone, subject to seasonal fluctuations. The initial monitoring results and the excellent preservation of fragile material, such as prehistoric leaves, at levels much closer to the present ground surface than the trackway, suggest that the observed decay in the wood from Trench 1 is unlikely to be a product of recent decay.

Worked wood representing human activity on the former line of the Sweet Track was found in Trench 1. Radiocarbon dating suggests that this was taking place more than half a millennium after the trackway went out of use. This raised the possibility that the line of the trackway as it approached Shapwick Burtle may have been memorialised in a way that was still a focus for human activity hundreds of years later. Trenches 2 and 3 contained some split pieces that could be reflective of human activity from a later date than the Sweet Track, but the poor preservation and lack of definitive toolmarks, mean that they could be entirely natural features. The charcoal and cut wood from Trench 4 are likely to represent activity at a date much later than the Sweet Track.

Monitoring over three years allowed a thorough analysis of the burial environment under different climatic conditions, with a wet summer in 2017 followed by an especially dry one in 2018. This shows the value of longer-term monitoring of sites, especially in view of potential future climate changes when more extreme events, like the summer of 2018, are expected to become more common.

Throughout the monitoring period there was no significant threat to the monument from desiccation, even in the dry summer of 2018. Anoxic conditions were maintained at the level of the trackway in all the years. However, the later worked wood in Trench 1 and the worked wood in Trench 4 were closer to the ground surface and the water table did go below them during the summer months. This shows that, although the site doesn't benefit from the dedicated pumping system that exists further north in the nature reserve, the generally high water table generated by the reserve management and the presence of a large nearby reedbed, both appear to create a fairly high water table even in a very dry summer.

The membrane had no significant effect on the burial environment and neither method of its insertion managed to help retain moisture in the summer months. Evapotranspiration remained the crucial driver lowering the groundwater in the summer and early autumn months and the trees on the eastern edge of the site had a more significant effect than the membrane, lowering the water table on that side of the field.

The desiccation of the upper 50cm of peat is a potential cause for concern as it will lead to a slow peat wastage, with the estimated loss of 2% of the organic matter each year. That will bring the ground surface down towards the Sweet Track over time but may not affect the position of the groundwater table in relation to the trackway.

The lowered summer water table and the gradual loss of organic matter in the upper layers may be a significant threat to early prehistoric waterlogged deposits where they rise up against the edges of the sand island and are therefore closer to the surface. Radiocarbon dating of the numerous bog oaks recovered from just below the field surface (Moir and Tyers forthcoming) would be beneficial in establishing the date of the at risk archaeology. The Mesolithic wetland/dryland edge project has already shown the significant potential of the fringes of the sand island (Bell *et al.* 2015).

The prospects for the continuing survival of the Sweet Track in the coming decades in this location appear very favourable. This positive conclusion is due to the resilience of the local water table in the Shapwick Heath Reserve, probably influenced by the presence of the nearby extensive reedbeds. Wetland monuments in other locations and in greater proximity to the ground surface are unlikely to be in such a favourable situation. This is reflected in the findings of the MARISP project (Brunning 2013) and in monitoring of the burial environment over the same period as the Sweet Track work at the nearby site of Glastonbury Lake Village. Although both sites are only a few miles apart in the same river floodplain, the upper levels of the waterlogged deposits at the Lake Village were shown to be potentially at risk of desiccation in extreme dry summers such as that of 2018 (Brunning et al 2020).

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9. APPENDICES

Appendix 1 Wiring of GP2 loggers

Wiring of the GP2 loggers

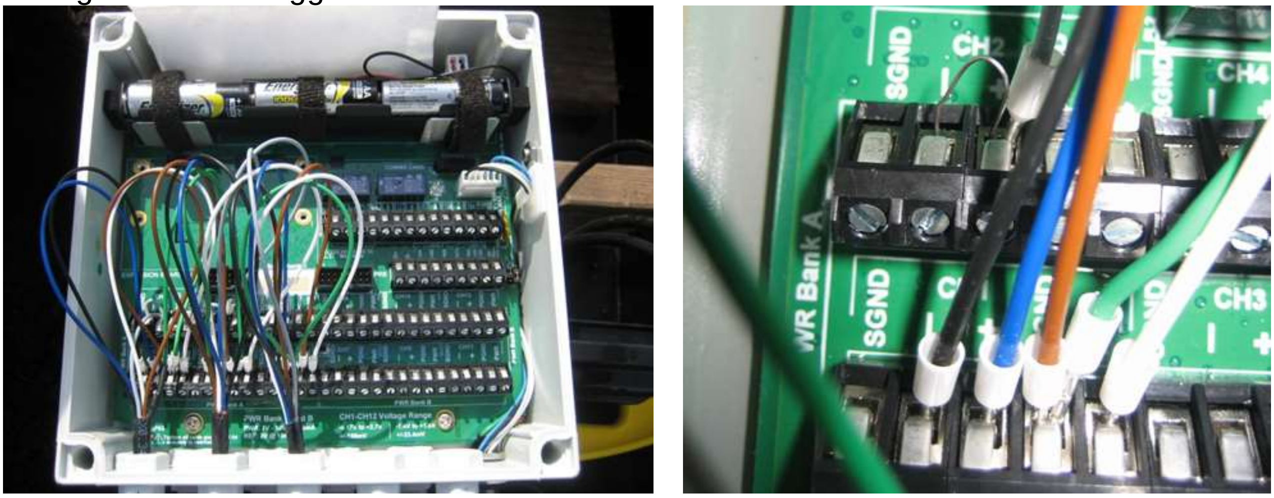

Figure A1: Wiring of the GP2 loggers. The sensor at 50 cm depth is connected to channels CH1 and CH2, 100 cm is connected to CH3 and CH4, and 150 cm is connected to CH5 and CH6. The channels CH2, CH4, and CH6 include a wire-link, which is necessary for temperature measurements. On the picture to the right, the wire link is seen as a thin metal wire, which was the only wire available during installation. Three of the temperature sensors have stopped working for unknown reasons, and it is suggested to check the wire-links and possibly replace the thin metal wire with an isolated copper wire.

Appendix 2 field and laboratory measurements

Field measurements during installation in March 2017 and laboratory measurements on samples

During the installation of equipment in March 2017, ring and bulk samples were taken from different soil strata for analysis in the laboratory. The results from these analyses are presented in Table A1. The weight of water, organics and inorganics in the samples have been recalculated to volume, using densities of 1 g/cm^3 for the water, 1.5 g/cm^3 for organic material, and 2.65 g/cm^3 for inorganic material (Matthiesen et al. 2015) – Figure A2 (upper 3 graphs). The total volume of the ring samples is 100 cm^3, which makes it possible to also calculate the total porosity and the volume of air/gas in the samples (Figure A2, lower graphs, left and middle). Bulk samples from the test pit were used to study the reactivity of the peat material under controlled conditions in the laboratory (Figure A2, lower, right graph).

			Total content in ring			Rel. to dry weight		Relative to volume				
Profile	Depth	Volume	Water	Organic	Inorganic	Water	LOI	Water	Organic	Inorganic	Air	Porosity
	(cm)	(cm^3)	g	g	g	(%w/dw)	(%w/dw)	(%vol)	(%vol)	(%vol)	(%vol)	(%vol)
Test pit	25	100	68.59	19.73	4.94	278	80	68.6	13.2	1.9	16.4	85.0
Test pit	50	100	80.68	10.58	0.93	701	92	80.7	7.1	0.4	11.9	92.6
Test pit	75	100	87.94	9.98	0.64	828	94	87.9	6.7	0.2	5.2	93.1
Test pit	100	100	81.84	10.37	0.67	741	94	81.8	6.9	0.3	11.0	92.8
Test pit	125	100	81.79	8.08	0.72	929	92	81.8	5.4	0.3	12.6	94.3
Test pit	150	100	78.78	7.76	0.73	928	91	78.8	5.2	0.3	15.8	94.6
A1 (from corer)	50	100	80.35	12.50	1.04	593	92	80.4	8.3	0.4	10.9	91.3
A1 (from corer)	100	100	89.38	8.92	0.55	944	94	89.4	5.9	0.2	4.5	93.8
A1 (from corer)	150	100	90.04	9.60	0.73	872	93	90.0	6.4	0.3	3.3	93.3
A2 (from corer)	50	100	84.69	13.68	2.25	532	86	84.7	9.1	0.8	5.3	90.0
A2 (from corer)	100	100	88.95	9.01	0.53	932	94	89.0	6.0	0.2	4.8	93.8
A2 (from corer)	150	100	90.59	9.76	0.54	880	95	90.6	6.5	0.2	2.7	93.3
B2 (from corer)	50	100	70.26	12.68	1.13	509	92	70.3	8.5	0.4	20.9	91.1
B2 (from corer)	100	100	86.11	9.61	1.10	804	90	86.1	6.4	0.4	7.1	93.2
B2 (from corer)	150	100	92.62	9.03	0.88	935	91	92.6	6.0	0.3	1.0	93.6

Table A1: Results from ring samples. w/dw means the weight relative to the dry weight of the sample.

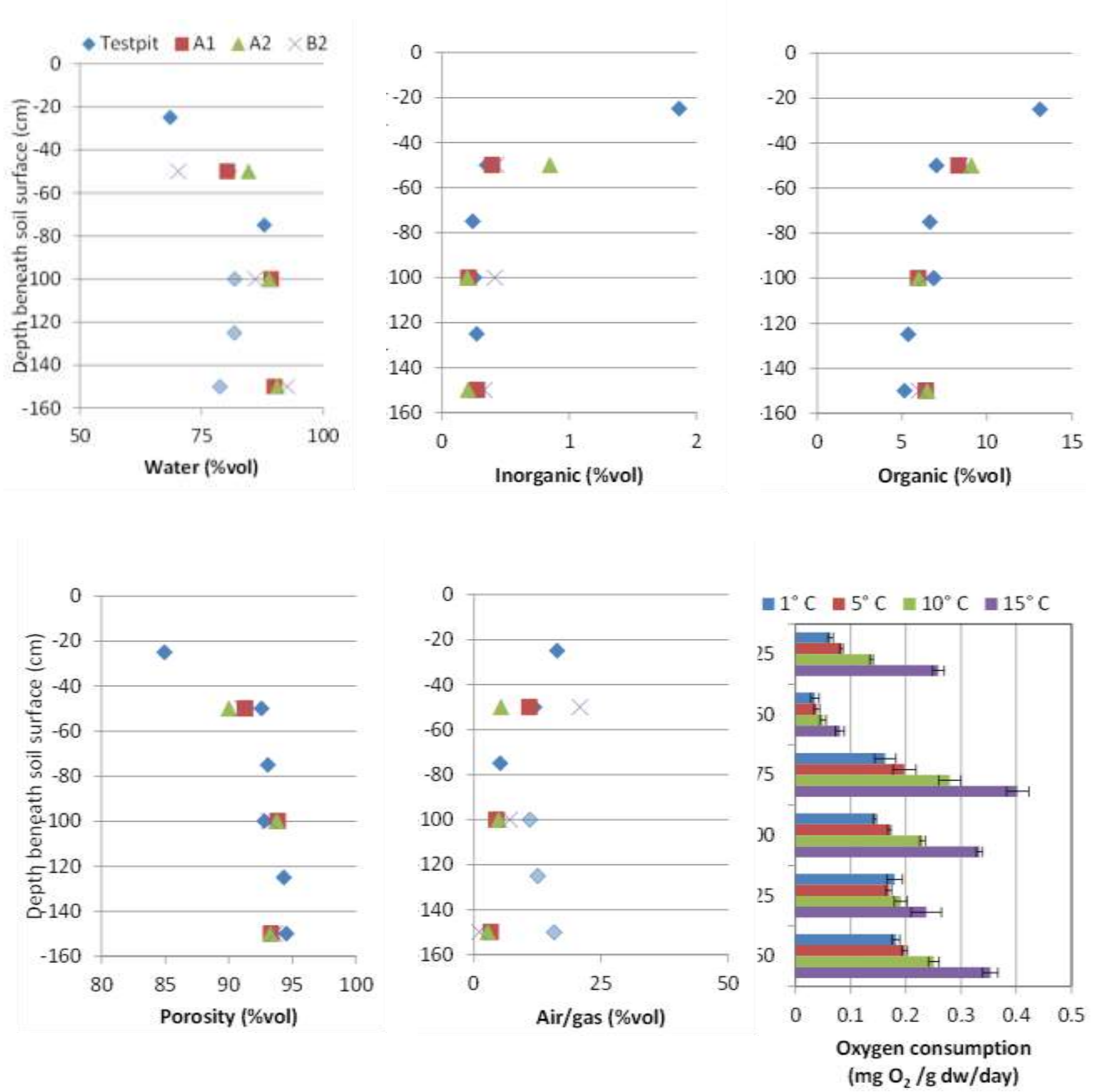

Figure A2. Results from ring and bulk samples from 30th March 2017. Results from ring samples (upper three and lower left/middle graphs) are recalculated to %vol. Results for oxygen consumption are given as mg O_2 consumed by 1 g sample (dry weight) during 1 day.

The results show an increasing porosity and water content with depth, while the organic and inorganic content is highest in the upper layers. The results from the test pit and from the three core samples are similar, except that the deeper samples from the test pit have somewhat lower water contents and higher calculated air contents than samples from the core samples. It cannot be excluded that this is an artefact, as there is some uncertainty connected to the results from ring samples. The rings need to be completely filled with undisturbed soil, and the loss of water during sampling and handling of the ring sample must be avoided. Even if the test pit was dug very fast, it cannot be excluded that some water has drained from the peat layers, especially in the deeper parts where the peat is more fibrous.

The results from reactivity measurements in the laboratory show that the reactivity increases with temperature. Q10 values between 1.2 and 2.8 are calculated from the data, i.e. the reactivity increases with a factor 1.2 to 2.8 for a 10 °C temperature increase (Hollesen and Matthiesen 2015). The measured reactivity is high for all the soil layers (up to 0.4 mg O_2/g dw/day) which is due to the samples consist of 80-95 % w/dw organic matter. For comparison the reactivity measured for organic soil material from Bryggen was < 0.1 mg/g gw/day even for soil with 45% w/dw organic material. This means that oxygen penetrating into the ground at Sweet Track will soon be used to oxidize the peat material.

Results from field measurements in the test pit are given in Figure A3

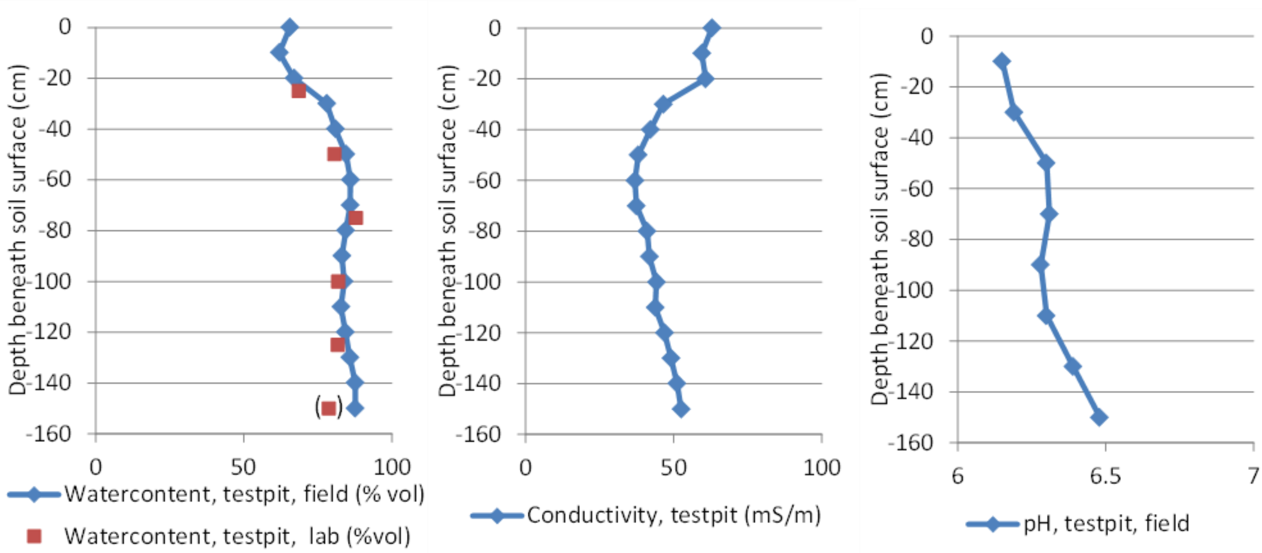

Figure A3: In situ measurements in test pit, 30th March 2017

The results show a good correspondence between the in situ measurements of water content and the laboratory measurements, apart from the deepest sample. The conductivity is distinctly higher in the uppermost 20-30 cm, but otherwise there are only modest variations. All pH measurements are between 6-6.5 which is normal for waterlogged soils.

Overall, the vertical variation for the parameters measured during the site visit and in the laboratory was limited, except that the uppermost soil layers at 25 cm depth showed a lower porosity, lower water content, higher conductivity and higher content of both organic and inorganic material. This is all due to the upper peat layers being more decomposed and less structured than the deeper layers. The deposits at 50 cm depth were the least reactive (Figure A2, lower right) probably because they are also partly degraded and there is only a limited supply of “fresh” organic material at this depth

Appendix 3 Wood species table

Wood species table for the Sweet Track excavation 100/2016

Wood No.	Trench	Description/comment	Species
1	1	Half split piece	*Betula* sp.
2	1		*Betula* sp.
3	1	Half split fragment, possibly cut	*Corylus avellana*
4	1		*Betula* sp.
5	1	Cut roundwood rod	*Corylus avellana*
6	1		*Betula* sp.
7	1		*Betula* sp.
8	1	Half split fragment	*Betula* sp.
9	1		Bark
10	1	Small peg	*Quercus sp.*
11	1	Cut roundwood, small stake	*Corylus avellana*
12	1		*Corylus avellana*
13	1		*Corylus avellana*
14	1	Radial splitting waste	*Fraxinus excelsior*
15	1	Woodchip	*Corylus avellana*
16	1	Split fragment	*Fraxinus excelsior*
17	1		*Ilex aquifolium*
18	1	Radial offcut	*Fraxinus excelsior*
19	1	Woodchip	*Quercus sp.*
20	1	Radial splitting waste	*Fraxinus excelsior*
21	1	Radially split offcut	*Quercus sp.*
22	1	Tangential plank fragment	*Fraxinus excelsior*
23	1	Woodchip	*Quercus sp.*
24	1	woodchip	*Quercus sp.*
25	1	woodchip	Betulaceae
26	1	Split timber	*Fraxinus excelsior*
27	1	Radially split fragment	*Fraxinus excelsior*
28	1	Radially split fragment	*Fraxinus excelsior*
29	1	Woodchip	*Fraxinus excelsior*
30	1	Woodchip/offcut	*Corylus avellana*
31	1	Possible artefact	*Ilex aquifolium*
32	1	stake	*Corylus avellana*
33	1		*Corylus avellana*
34	1		*Fraxinus excelsior*
35	1	Radial splitting waste	*Fraxinus excelsior*
36	1		*Corylus avellana*
37	1	Woodchip	*Fraxinus excelsior*
38	1		*Corylus avellana*
39	1		*Corylus avellana*
40	1	woodchip	Indet: cf. *Betula* sp.

Wood No.	Trench	Description/comment	Species
41	1	Woodchip	*Fraxinus excelsior*
42	1	Woodchip?	*Fraxinus excelsior*
43	1	Radial plank fragment	*Fraxinus excelsior*
44	1	Woodchip	*Quercus sp.*
45	1	Radial splitting waste	*Quercus sp.*
46	1	Half split fragment	*Corylus avellana*
47	1		*Corylus avellana*
48	1		*Corylus avellana*
49	1	Radial plank	*Fraxinus excelsior*
50	1		*Corylus avellana*
51	1	Woodchip	*Fraxinus excelsior*
52	1	Woodchip	*Ilex aquifolium*
53	1	Woodchip	*Corylus avellana*
54	1		*Corylus avellana*
55	1		*Corylus avellana*
56	1		*Corylus avellana*
57	1	Woodchip?	*Fraxinus excelsior*
58	1	Radial plank fragment	*Fraxinus excelsior*
59	1	woodchip	*Corylus avellana*
60	1	Woodchip	*Corylus avellana*
61	1	woodchip	*Corylus avellana*
62	1	woodchip	*Fraxinus excelsior*
63	1	woodchip	?bark
64a	1	Woodchip	*Corylus avellana*
64b	1	Offcut	*Corylus avellana*
65	1	Woodchip?	*Corylus avellana*
66	1		*Fraxinus excelsior*
67	1	woodchip	*Corylus avellana*
68	1	woodchip	Indet: cf. *Betula* sp.
69	1	Narrow radial plank	Indeterminate diffuse porous
70	1	Woodchip	*Quercus sp.*
71	1	Woodchip/offcut	*Corylus avellana*
72	1	Radial plank	*Fraxinus excelsior*
73	1	Cut split piece	*Corylus avellana*
74	1	Stake tip	Indeterminate
75	2		*Bark*
76	2	Woodchip?	?bark
77	2		*Betula/Alnus*
78	2	Woodchip?	?bark
79	2	Woodchip?	?bark
80	2		*Fraxinus excelsior*
81	3	Very decayed fragment	
82	3	Very decayed fragment	

Wood No.	Trench	Description/comment	Species
83	3		bark
84	4	Cut roundwood	*Fraxinus excelsior*
85	4		*Alnus/Corylus*
86	4		*Fraxinus excelsior*
87	4		bark
88	4	Bark woodchips a, b and c	bark
89	4		bark
90	4		*Alnus/Corylus*
91	4	Irregular lump	*Fraxinus excelsior*
92	4	Split fragment	*Fraxinus excelsior*
93	4	Tiny fragment	?bark
94	4	Small fragment, possibly a peg	Indeterminate
95	4	Split log	
96	4	Rotted piece	Indeterminate
97	4	Irregular lump	*Alnus glutinosa*
98	4	Small stake?	*Fraxinus excelsior*
99	4	Number not used?	
100	4	Number not used?	
101	4	Split log	*Fraxinus excelsior*
102	3	Split fragment	*Taxus baccata*
103	1	woodchip	*Corylus avellana*
104	1	woodchip	*Fraxinus excelsior*
105	1	woodchip	
106	1	woodchip	*Quercus sp.*
107	1	woodchip	*Fraxinus excelsior*
108	1	woodchip	*Fraxinus excelsior*
109	1	woodchip	*Fraxinus excelsior*
110	1	woodchip	*Fraxinus excelsior*
111	1	woodchip	*Corylus avellana*
112	1	woodchip	*Corylus avellana*
113	1	woodchip	*Fraxinus excelsior*
114	1	woodchip	*Fraxinus excelsior*
115	1	woodchip	*Corylus avellana*
116	1	woodchip	*Corylus avellana*
117	1	woodchip	
118	1	woodchip	*Fraxinus excelsior*
119	1	woodchip	*Corylus avellana*
120	1	woodchip	*Fraxinus excelsior*
121	1	woodchip	Indet: cf. *Betula* sp.
122	1	woodchip	*Quercus sp.*
123	1	woodchip	*Fraxinus excelsior*
124	1	woodchip	*Fraxinus excelsior*
125	1	woodchip	*Fraxinus excelsior*
126	1	woodchip	*Quercus sp.*

Wood No.	Trench	Description/comment	Species
127	1	woodchip	*Fraxinus excelsior*
128	1	woodchip	*Fraxinus excelsior*
129	1	woodchip	*Fraxinus excelsior*
130	1	woodchip	*Fraxinus excelsior*
131	1	woodchip	*Fraxinus excelsior*
132	1	woodchip	*Quercus sp.*
133	1	woodchip	*Quercus sp.*
134	1	woodchip	*Fraxinus excelsior*
135	1	woodchip	*Fraxinus excelsior*
136	1	woodchip	*Fraxinus excelsior*
137	1	woodchip	
138	1	woodchip	*Fraxinus excelsior*
139	1	woodchip	*Fraxinus excelsior*
140	1	woodchip	*Fraxinus excelsior*
141	1	woodchip	
142	1	woodchip	*Fraxinus excelsior*
143	1	woodchip	*Fraxinus excelsior*
144	1	woodchip	
145	1	woodchip	
146	1	woodchip	
147	1	woodchip	
148	1	woodchip	
149	1	woodchip	
150	1	woodchip	
151	1	woodchip	
152	1	woodchip	*Quercus sp.*
153	1	woodchip	
154	1	woodchip	
155	1	woodchip	
156	1	woodchip	*Quercus sp.*
157	1	woodchip	*Quercus sp.*
158	1		bark
159	1	woodchip	*Quercus sp.*
160	1		bark
161	1		bark
162	1		bark
163	1		bark

Gallery

Right: Excavating the perimeter bund parallel to the Sweet Track. In this compartment (B) the bund was being keyed into the clay (just visible at the base of the cut) underlying the peat

Below: The membrane stretched over compartment A, leaving a narrow strip in the middle to allow water penetration. The machined surface was slightly angled downwards towards this gap.