

A 3000-year multiproxy palaeoclimate record from Killorn Moss, Stirlingshire, Scotland

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SUMMARY

Peatlands across the United Kingdom and Europe represent an important source of palaeoenvironmental and palaeoclimatological data for the Holocene time period. Here we derive a detailed 3000-year record of inferred changes in water table from the raised bog at Killorn Moss in central Scotland, employing a multiproxy approach. Proxies are compared and contrasted, and the merits of a multiproxy approach are highlighted. Ten changes to wetter conditions supported by at least two proxies are evident at Killorn, with substantial shifts related to the Sub-boreal/Sub-atlantic transition and post Roman and Dark Age deteriorations. Inferred changes in climate are compared with a local record from another raised bog and with more geographically widespread locations highlighting corresponding events, but also evidencing the importance of robust dating.

KEY WORDS: climate, Holocene, macrofossil, peat, testate amoebae

INTRODUCTION

Ombrotrophic (rain-fed) peatlands provide valuable palaeoclimate and palaeoecological archives for the early–mid to late Holocene, offering decadal to centennial scale resolution. Research effort and consequent records were originally concentrated in NW Europe (Barber *et al.* 1994, Blundell & Barber 2005, Langdon & Barber 2005, Charman *et al.* 2006) but later spread globally across mid–high latitudes (Hughes *et al.* 2006, Nichols & Huang 2012, Liu *et al.* 2017, Blundell *et al.* 2018, Liu *et al.* 2019). Reconstructions of bog surface wetness have been shown in NW Europe to reflect summer moisture deficits related primarily to changes in precipitation (Charman *et al.* 2009), with recent centuries showing widespread drying across the region (Swindles *et al.* 2019). Proxy analyses employed to determine bog surface wetness have typically included testate amoebae, macrofossil and humification analyses although other proxies such as isotopes have been occasionally used. Testate amoebae records are typically used together with a transfer function to transform species assemblages into quantitative estimates of water table depth (Charman *et al.* 2007), whereas macrofossil records commonly provide semi-quantitative output via either multivariate statistics or weightings (Hydroclimatic Index) to relate each individual taxon to its relative water table tolerance (Daley & Barber 2012). Humification is

typically recorded in the field using the von Post scale (von Post 1924) or via light absorbance of an alkali extraction (Blackford & Chambers 1993) in the laboratory. Changes in climate, although predominant, are not the sole influence upon the three main analyses typically used and, therefore, a multiproxy approach has previously been advocated (Blundell & Barber 2005, Langdon & Barber 2005) to identify and rectify erroneous interpretations from an individual proxy by using the remaining ones. An increasing number of peat-based archives has led to numerous attempts to provide regional or national compilations, primarily using testate amoebae transfer function data alone (Charman *et al.* 2006, Swindles *et al.* 2013, Swindles *et al.* 2019), and to a lesser extent with multiple proxies (Langdon & Barber 2005, Blundell *et al.* 2008). Combining proxies that consist of semi-quantitative and quantitative outputs into a meaningful record for the wider scientific community and society in general is challenging, but a multiproxy approach remains extremely valuable for deriving robust records from peatlands. In this study a multiproxy approach employing testate amoebae, macrofossil and humification analyses is used to derive a 3000-year-old palaeoclimate record from a raised peatland in central Scotland (UK). The proxies are examined relative to each other to provide a robust and detailed archive of bog surface wetness that is compared to other regional peat-based and non-peat-based records to determine its relation to changes in climate.



METHODS

Site description

Killorn Moss is a raised bog, 34.9 hectares in extent, situated south of the River Forth in central Scotland (56° 8' 15.47" N, 4° 13' 7.23" W). To the north is the expansive raised bog complex of Flanders Moss studied by Haslam (1987) and 2 km to the east is Shirgarton Moss (Figure 1) as examined by Langdon & Barber (2005). These three bogs are all part of a former extensive raised bog system that used to cover much of the area of the broad flat-bottomed valley known as the 'Carse of Stirling' before succumbing to various damaging actions including substantial peat removal to establish farmland in the 18th century (Pickett 2018).

Surface vegetation is dominated by *Calluna vulgaris* and *Eriophorum vaginatum*, although there are open areas of *Sphagnum* composed of *Sphagnum rubellum*, *Sphagnum magellanicum*, *Sphagnum papillosum* and *Sphagnum tenellum*. In the wettest areas *Drosera rotundifolia*, *Vaccinium oxycoccos*, *Narthecium ossifragum* and *Andromeda polifolia* are evident. Killorn Moss has a well-developed rand (the steeply sloping marginal region; Godwin & Conway 1939) surrounded by birch (*Betula pubescens*) trees. Aerial imagery does provide evidence of some drainage ditches, cutting and encroachment of woodland. Annual precipitation, and mean minimum and mean maximum daily temperatures recorded for nearby Stirling (1991–2020; <https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages>) are ~1018 mm, 5.8 °C and 13.3 °C respectively.

Field methods

A core was taken in a central location, from a low lawn microform composed of *Sphagnum magellanicum*, *Sphagnum* section *Acutifolia* and *Sphagnum* section *Cuspidata*. Peat was recovered from the site using a monolith tin (10 × 10 × 40 cm) for depths of 0–40 cm and a wide-bore (9 cm) 30 cm long Russian corer (Barber 1984) thereafter, down to 3 metres with overlaps of at least 5 cm. All core samples were placed in sealed plastic bags and refrigerated at 4 °C.

Recovery, sampling and laboratory analyses

Recovery and sampling

The peat core was sub-sampled for humification (4 cm³), macrofossils (4 cm³) and testate amoebae (2 cm³). Sampling resolution was initially every 4 cm over the depth range 0–248 cm for all proxies. Samples were also removed for Accelerator Mass Spectrometry (AMS) radiocarbon dating. Depths for

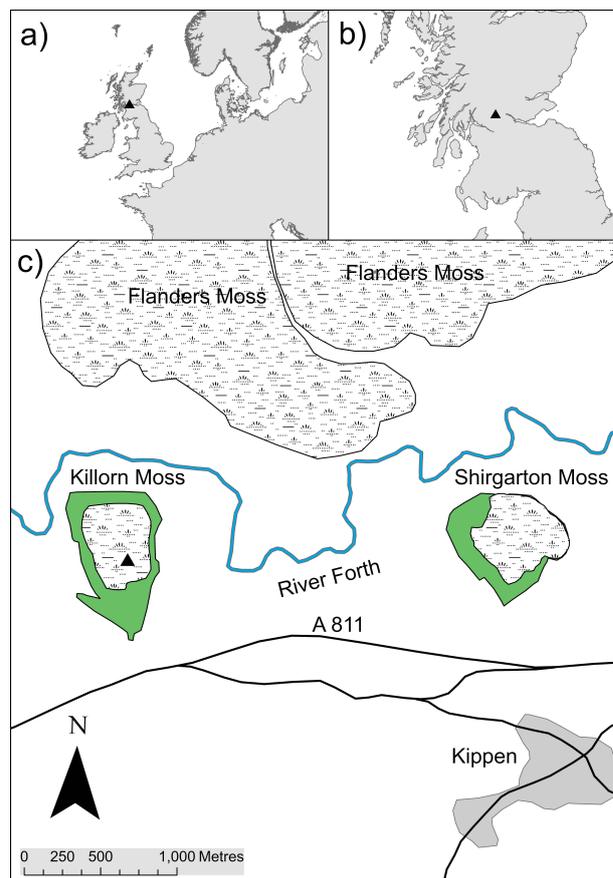


Figure 1. The location of Killorn Moss a) internationally, b) nationally and c) in relation to Shigarton Moss. The green shading surrounding Killorn Moss and adjacent to Shigarton Moss denotes tree cover.

radiocarbon dates were determined after the multiproxy analyses were completed, and included levels demonstrating substantial shifts in macrofossil taxa representing changes to wetter conditions. Later examination of records together with extra AMS dates led to further analysis of both testate amoebae and macrofossils, from 252–300 cm at 4 cm resolution and from 52–132 cm with an increase in resolution to 2 cm. Humification samples were not further examined at this later time because decomposition may have occurred since initial sampling.

Chronology

Major changes in the macrofossil stratigraphy were dated using a total of 12 AMS radiocarbon dates (Figure 2 and Table 1). Samples analysed by the NERC Radiocarbon Laboratory were derived from 1 cm³ blocks of peat washed with deionised water in a 125 µm sieve. *Sphagnum* leaves, branches or stems were selected, washed and visually examined to

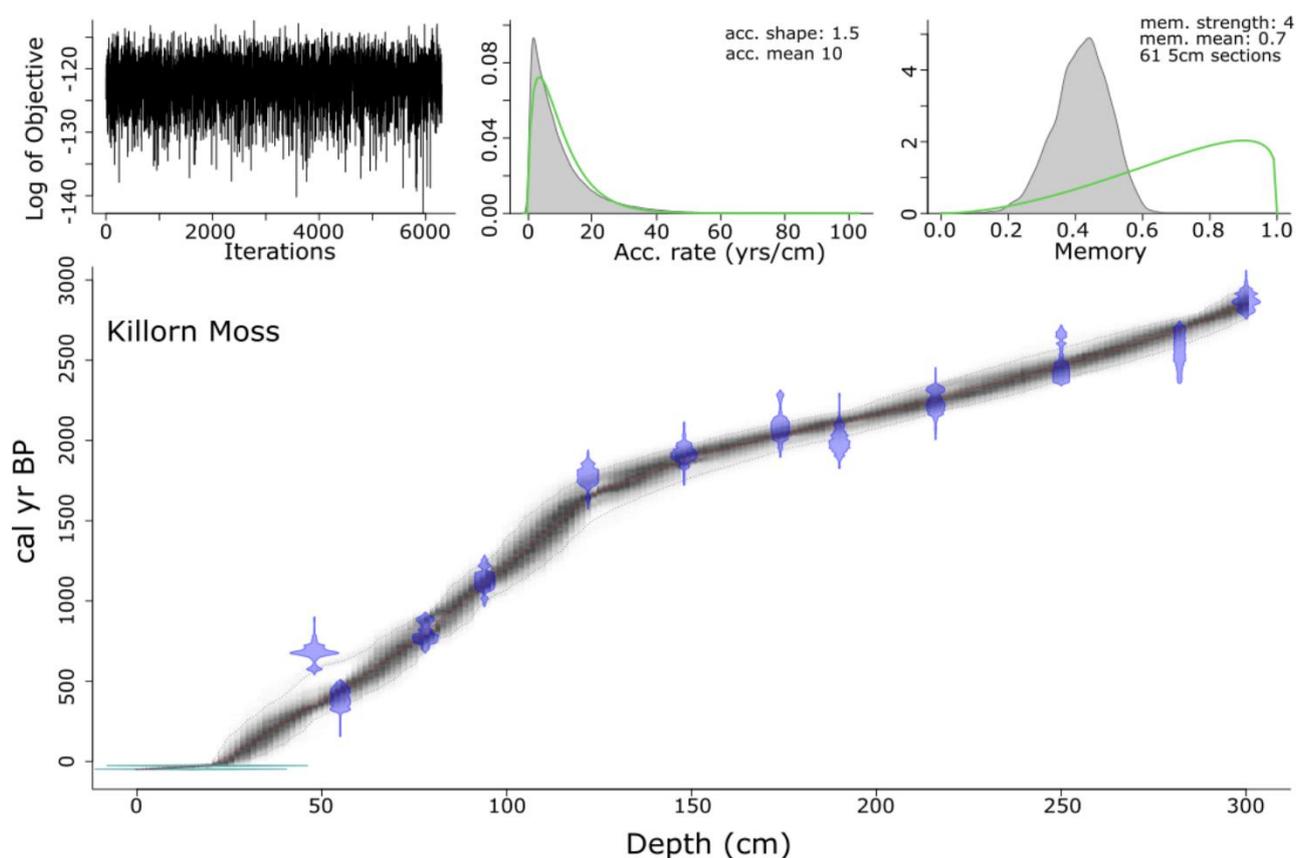


Figure 2. ‘Bacon’ based Bayesian age-depth model for the core from Killorn Moss. The three upper charts denote, from left to right, the stability of the Markov Chain Monte Carlo iterations (>1000 iterations) and the prior (green line) and posterior (grey shading) accumulation rate and memory employed. In the lower chart, blue shading shows age distributions of calibrated AMS ^{14}C dates, green shading denotes calendar dates incorporated into the model from Spheroidal Carbonaceous Particles (SCPs) data, and grey shading denotes the posterior age-depth model bounded by grey dots showing the 95 % probability intervals of the model.

minimise any potential contamination. Samples analysed by Beta Analytic Inc. were bulk 1 cm^3 volumes of peat (Table 1).

Spheroidal Carbonaceous Particles (SCPs) were prepared and counted using the method detailed by Rose (1990, 1994) with minor modifications as used by Blundell *et al.* (2008). The abundance of SCPs counted at $\times 400$ magnification was expressed as SCPs gDM^{-1} (number of particles per gram of dry mass of peat). Age determinations were based on the peak of the characteristic curve produced (Rose *et al.* 1995).

An age-depth model was produced using the ‘Bacon’ accumulation model (Blaauw & Christen 2011) in R (R Core Team 2022). This model uses Bayesian statistics to determine Bayesian accumulation histories using radiocarbon dates and prior information. Prior information regarding peat accumulation rate and its potential to vary (Figure 2) is accounted for, providing a robust age-depth model.

A calendar estimated age from SCP analysis was also employed in the model. Bacon output provides estimates for every 1 cm interval of total chronological error with maximum and minimum ages within the ‘modelled age range’ (MAR, based on 95 % confidence ranges) together with ‘maximum age probabilities’ (MAPs) providing the most likely date. Following Turner *et al.* (2014) and Blundell *et al.* (2016), dates quoted for Killorn Moss in the Results section are MAPs followed by the MAR value in subscript text, and thereafter the MAP dates are used alone.

Proxy analyses

Macrofossil analyses were carried out using the Quadrat and Leaf Count technique (QLC; Barber *et al.* 1994). Nomenclature follows Daniels & Eddy (1990) for *Sphagnum* mosses, Smith (2004) for other bryophytes, and Stace (1991) for vascular plants. A Hydroclimatic Index (HCI) was calculated by

Table 1. AMS radiocarbon dates, calibrated (2 δ range).

Laboratory number	Depth (cm)	Material	AMS radiocarbon date BP (uncal.)	1 δ error	Cal. Range (2 δ) BP	Cal. Range (2 δ) CE/BCE
AA-42381	48	<i>Sphagnum</i> leaves/branches/stems	733	45	731 – 563	1219 – 1387
AA-42382	55	<i>Sphagnum</i> leaves/branches/stems	334	36	478 – 308	1472 – 1642
AA-42383	78	<i>Sphagnum</i> leaves/branches/stems	875	37	905 – 689	1045 – 1261
AA-42384	94	<i>Sphagnum</i> leaves/branches/stems	1203	37	1264 – 997	686 – 953
AA-42385	122	<i>Sphagnum</i> leaves/branches/stems	1845	39	1865 – 1626	85 – 324
AA-42386	148	<i>Sphagnum</i> leaves/branches/stems	1965	39	1994 – 1751	-44 – 199
AA-42387	174	<i>Sphagnum</i> leaves/branches/stems	2105	42	2297 – 1943	-347 – 7
AA-42388	190	<i>Sphagnum</i> leaves/branches/stems	2035	42	2110 – 1845	-160 – 105
AA-42389	216	<i>Sphagnum</i> leaves/branches/stems	2246	49	2346 – 2133	-396 – -183
UBA-18674	250	Bulk peat	2417	34	2698 – 2349	-748 – -399
UBA-18675	282	Bulk peat	2479	37	2721 – 2370	-771 – -420
UBA-20134	300	Bulk peat	2773	33	2952 – 2782	-1002 – -832



weighted averaging ordination after Dupont (1986) and Daley & Barber (2012) with each taxon weighted on the basis of their relative positions along the bog water-table gradient. Weightings were as follows: unidentified organic matter (UOM) = 8, Ericaceae wood and roots = 7, *Aulacomnium palustre* = 7, *Polytrichum* spp. = 7, *Eriophorum vaginatum* = 6, monocotyledons (undifferentiated) = 6, *Trichophorum cespitosum* = 6, *Sphagnum* section *Acutifolia* = 4, *Sphagnum austinii* = 4, *Sphagnum papillosum* = 3, *Sphagnum magellanicum* = 3, *Eriophorum angustifolium* = 2, *Rhynchospora alba* = 2, *Sphagnum* section *Cuspidata* = 1 and *Sphagnum cuspidatum* = 1.

Humification analyses were carried out in accordance with methods recommended by Blackford & Chambers (1993) using the chemical extraction of humic matter which was measured for light absorbance in a spectrophotometer at a wavelength of 550 nm. The extraction technique, which is routinely employed, has raised concern (Biester *et al.* 2014) as it may potentially alter the humic products that result. Species-dependent decomposition has also been noted as a potential concern when employing this method by Caseldine *et al.* (2000), Yeloff & Mauquoy (2006) and Hughes *et al.* (2012). This is partly mitigated here by our multiproxy approach, specifically by producing a full and detailed macrofossil record against which to check the humification results.

Samples for testate amoebae analysis were prepared and counted in accordance with methods outlined by Charman *et al.* (2000). The system of taxonomy here is directly related to the transfer function employed, meaning that water table reconstructions should not suffer from errors resulting from taxonomic inconsistencies between the modern training set and the palaeoecological data as highlighted by Payne *et al.* (2010). The weighted average (inverse deshrinking) version of the European transfer function developed by Charman *et al.* (2007) was employed using C2 software (Juggins 2007). One hundred tests were counted here and this is generally considered sufficient to provide representative samples (Payne & Mitchell 2009). Swindles *et al.* (2015) demonstrated that although most available testate transfer functions are poor at reconstructing actual absolute values of mean depth to water table, they are reliable in terms of shifts in direction to wetter or drier conditions. Swindles *et al.* (2015) therefore recommend stating standardised values, commonly z-scores, to avoid confusion with contemporary water-table data that report reliable magnitudes. Both are reported here. Macrofossil and testate amoebae data were plotted using the P4 plotting program (Blundell 2023).

RESULTS

Plant macrofossils and chronology

All 12 AMS dates and the single SCP date were employed to create the age-depth model in Bacon (Figure 2). The entire core examined here spans just less than 3000 years to ca. 905 MAR 810–1010 BCE. From 300 to 124 cm (ca. 900 MAR 806–1010 BCE to 280 MAR 155–440 CE) the macrofossil record is largely dominated by *Sphagnum austinii* and *Sphagnum* section (s.) *Acutifolia* with a high mean peat accumulation rate of ~6.6 yrs cm⁻¹, translating to only ~26 years between samples. Within zone KIL-a (ca. 900 MAR 806–1010 BCE to 775 MAR 832–676 BCE), Ericaceae macrofossils become dominant (Figure 3) together with UOM and evidence of *Aulacomnium palustre* moss, all of which is indicative of relatively dry surface conditions (Andrus *et al.* 1983, Hughes *et al.* 2000). Generally, there is a lowering of Ericaceae and UOM through zone KIL-b as *Sphagnum* moss dominates and switches between *Sphagnum austinii* and *Sphagnum* s. *Acutifolia*. *Sphagnum austinii* and the possible species contained within *Sphagnum* s. *Acutifolia* are likely to have overlapping water table tolerances, so these switches are not necessarily significant with respect to surface wetness. However, evidence of *Cenococcum*, *Scirpus cespitosus* and *Aulaconinum palustre* suggests relatively dry hummock conditions (Okland 1990, Lamentowicz *et al.* 2008).

Evidence of *Eriophorum angustifolium* and *Sphagnum* s. *Cuspidata* in zone KIL-c implies a change towards wetter conditions as the former is found generally in pool habitats (van der Molen & Hoekstra 1988), as are most of the species from section *Cuspidata* such as *Sphagnum cuspidatum*, *Sphagnum recurvum* and *Sphagnum pulchrum* (Andrus *et al.* 1983, Rydin 1993). The presence of *Eriophorum vaginatum* and increased Ericaceae towards the end of the zone suggests a later move towards drier surface conditions. Levels of *Sphagnum* s. *Cuspidata* increase steadily through KIL-c from 206 cm (ca. 250 BCE MAR 341–161 BCE) and increase more rapidly at 186 cm (ca. 140 BCE MAR 210–48 BCE) peaking at 176 cm (ca. 95 BCE MAR 168–3 BCE) and, together with evidence of both *Rhynchospora alba* and *Eriophorum angustifolium*, mark a substantial increase in water table levels as a pool environment is formed. Zone KIL-e is dominated by *Sphagnum austinii* until renewed consistent presence of *Sphagnum* s. *Cuspidata* from 130 cm (ca. 220 CE MAR 96–366 CE) that peaks in association with *Rhynchospora alba*, a species of *Cyperaceae* known to inhabit a narrow water table niche around pool environments (Okland 1990, Hammond *et al.* 1990, van der Molen *et al.* 1994). Mean accumulation rates

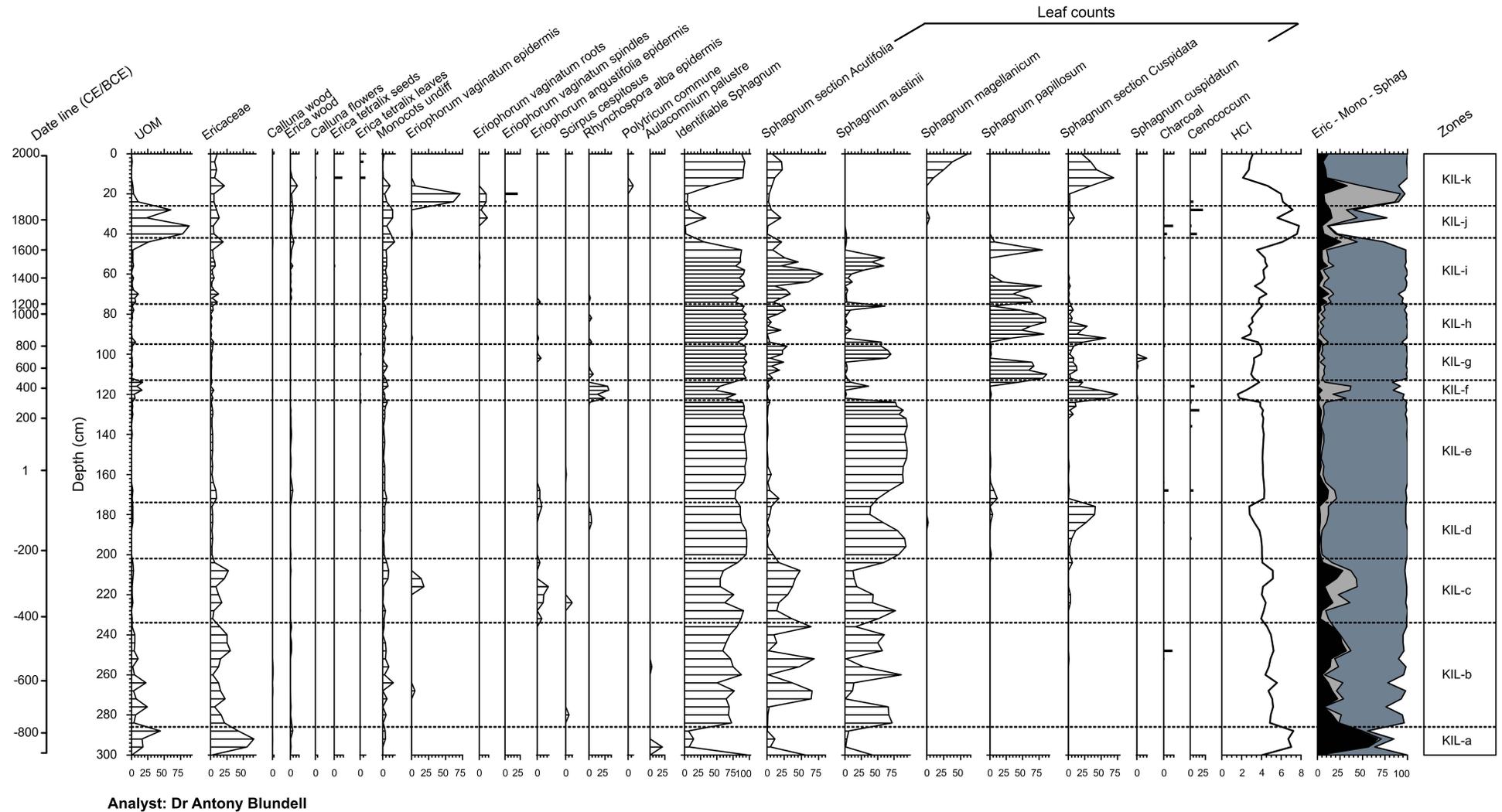


Figure 3. Macrofossil diagram for the Killorn Moss core. Peat components are derived from averaged quadrat counts under low-power magnification ($\times 10$). Leaf counts are a breakdown of the % identifiable *Sphagnum* and consist of proportions based on a random selection of leaves (100 per sample interval where possible) identified at high magnification ($\times 400$). Bar graphs are absolute counts. The Hydroclimatic Index (HCI) is also displayed, as is the percentage of the peat made up of Ericaceae (Eric), Monocotyledons (Mono) and *Sphagnum* (Sphag).

from 124 to 20 cm (ca. 280 CE _{MAR 155–440 CE} to 1975 CE _{MAR 1965–1980 CE}) are reduced to ca. 16.3 yrs cm⁻¹ in association with successions of different *Sphagnum* taxa. In zone KIL-f *Sphagnum* s. *Cuspidata*, although still in evidence, is largely succeeded first by *Sphagnum papillosum* and subsequently by *Sphagnum austinii* into KIL-g. Renewed increase in *Sphagnum* s. *Cuspidata* from 95 cm (ca. 820 CE _{MAR 689–947 CE}) peaking at 92 cm (ca. 880 CE _{MAR 742–1005 CE}) implies expansion of a pool area suggesting wetter conditions. This is followed by a similar succession by *Sphagnum papillosum* and briefly *Sphagnum austinii* followed again by *Sphagnum papillosum* in KIL-h. *Sphagnum* s. *Acutifolia* and *Sphagnum austinii* dominate KIL-l before an isolated peak in *Sphagnum papillosum* at 48 cm (ca. 1600 CE _{MAR 1386–1688 CE}). In KIL-j, substantial presence of UOM and evidence of charcoal points to possible damage by fire. KIL-k includes evidence of regrowth from *Eriophorum vaginatum*, a species known to return vigorously post fire (Rawes & Welch 1969, Ratcliffe 1964) that is succeeded by a pool environment with *Sphagnum* s. *Cuspidata*. From 19 cm to the surface the accumulation rate is extremely high (~1.2 yrs cm⁻¹) due to the lack of compression of the evident *Sphagnum* s. *Cuspidata* and *Sphagnum magellanicum* mosses. Changes in plant macrofossils reflecting a change to higher water tables and evident in the HCI are listed in Table 2.

Testate amoebae

A series of increases in *Archella flavum* and *Amphitrema wrightianum*, both indicators of relatively wet conditions, are evident in KIL-a and b replacing *Hyalosphenia subflava* and *Trigonopyxis arcuata* (Figure 4). A relatively minor increase in *Archella flavum* is evident at 286 cm (ca. 770 BCE _{MAR 832–676 BCE}) but is followed by more substantial increases of both *Archella flavum* and *Amphitrema wrightianum* from 278 cm (ca. 710 BCE _{MAR 791–610 BCE}) and later from 262 cm (ca. 600 BCE _{MAR 699–502 BCE}) with a low in depth to water table (DTWT) recorded at 248 cm (ca. 500 BCE _{MAR 610–411 BCE}). From 240–132 cm (covering parts of zones from KIL-b through to KIL-e) the taxa are mainly *Archella flavum*, *Amphitrema wrightianum*, *Diffugia pulex* and *Nebela militaris*. Some prominent features indicating change to higher water tables are increases in *Archella flavum* and *Amphitrema wrightianum* from 238 cm (ca. 440 BCE _{MAR 549–344 BCE}), the latter peaking at 224 cm (ca. 350 _{MAR 454–266 BCE}), and a relatively minor increase in *Amphitrema wrightianum* from 182 cm (ca. 120 BCE _{MAR 193–31 BCE}) peaking at 172 cm (ca. 70 BCE _{MAR 148 BCE–28 CE}).

A major change occurs at 127 cm (ca. 250 CE _{MAR 123–403 CE}) as taxa are dominated by *Archella flavum* and especially *Amphitrema wrightianum* through zones KIL-f to KIL-h implying a substantial decrease

Table 2. Depth (cm), maximum age probabilities (MAP) and modelled age range (MAR) for shifts to higher water tables recorded by each proxy from Killorn Moss. Bold typeface is used for events recorded by two or more of the three proxies.

Macrofossil HCI		Testate amoebae DTWT		Humification (detrended)	
Depth (cm)	Age (MAP and MAR)	Depth (cm)	Age (MAP and MAR)	Depth (cm)	Age (MAP and MAR)
53	1540 CE _{MAR 1339–1628 CE}	53	1540 CE _{MAR 1339–1628 CE}		
69	1300 CE _{MAR 1142–1446 CE}			70	1280 CE _{MAR 1122–1436 CE}
95	820 CE _{MAR 689–947 CE}	95	820 CE _{MAR 689–947 CE}	98	760 CE _{MAR 628–900 CE}
127	250 CE _{MAR 123–403 CE}	127	250 CE _{MAR 123–403 CE}	122	310 CE _{MAR 176–472 CE}
186	140 BCE _{MAR 210–48 BCE}			186	140 BCE _{MAR 210–48 BCE}
206	250 BCE _{MAR 341–161 BCE}	206	250 BCE _{MAR 341–161 BCE}	206	250 BCE _{MAR 341–161 BCE}
				214	290 BCE _{MAR 391–210 BCE}
238	440 BCE _{MAR 549–344 BCE}			234	410 BCE _{MAR 522–319 BCE}
				246	490 BCE _{MAR 599–397 BCE}
262	600 BCE _{MAR 699–502 BCE}	262	600 BCE _{MAR 699–502 BCE}		
278	710 BCE _{MAR 791–610 BCE}	278	710 BCE _{MAR 791–610 BCE}		
286	770 BCE _{MAR 832–676 BCE}	290	810 BCE _{MAR 885–704 BCE}		

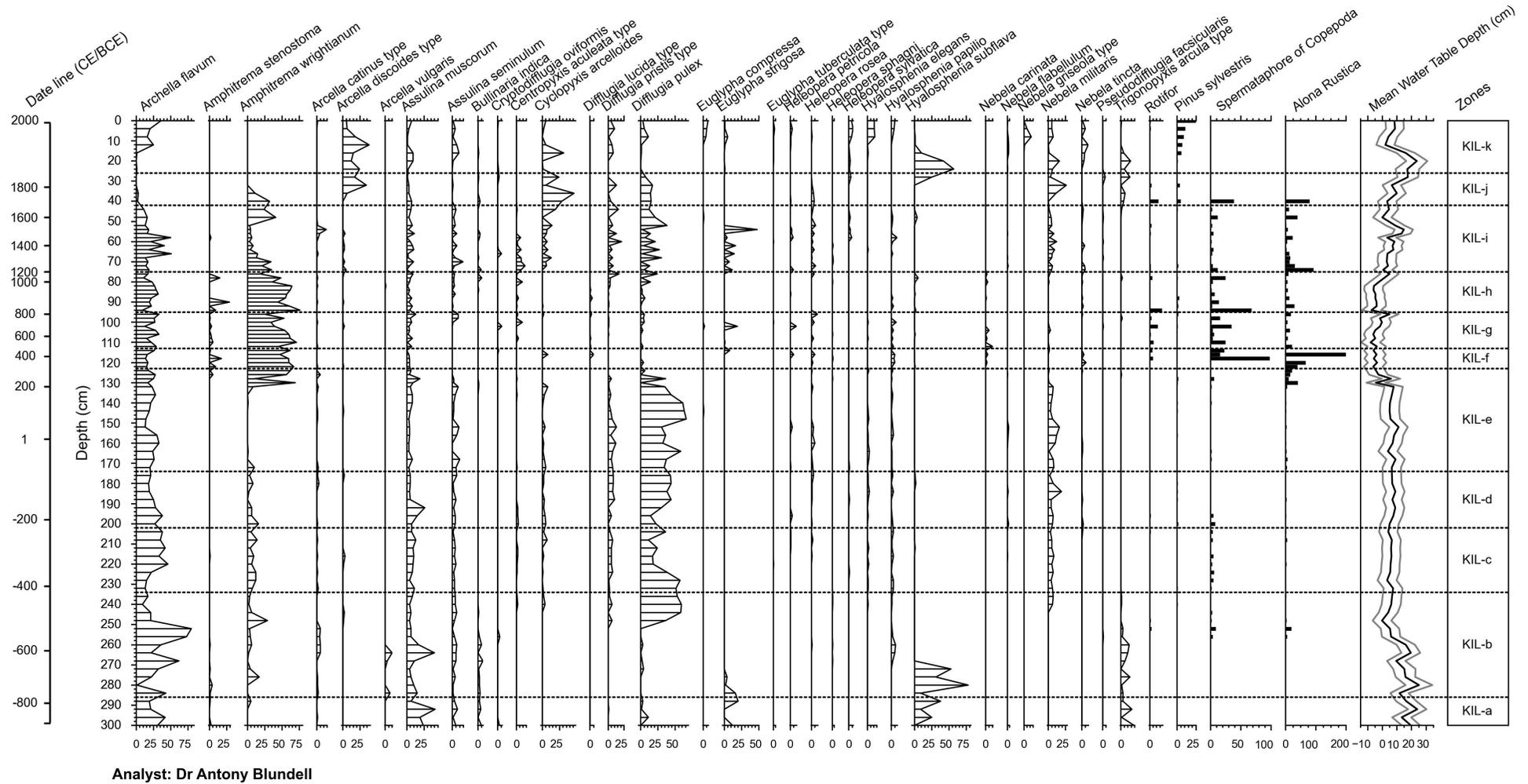


Figure 4. Testate amoebae diagram for Killorn Moss. All testate data are percentages of the total number counted per depth level. Bar graphs are absolute counts. Depth to water table reconstruction in centimetres from transfer function (Charman *et al.* 2007) together with associated errors derived from bootstrapping are displayed.



in DTWT. Variation within this is evident as a further substantial increase in *Amphitrema wrightianum* occurs from 95 cm (ca. 820 CE _{MAR 689–947 CE}). Increasing DTWT is evident after 81 cm (ca. 1090 CE _{MAR 983–1200 CE}) as these wet indicating taxa decline. A further decrease in DTWT is evident from 53 cm (ca. 1540 CE _{MAR 1340–1628 CE}) as *Amphitrema wrightianum* increases into KIL-j peaking at 48 cm (ca. 1600 CE _{MAR 1386–1688 CE}). Thereafter, *Cyclopyxis arcelloides* and a combination of *Hyalosphenia subflava* and *Arcella discoides* increase in tandem with signs of damage to the site seen in the macrofossil record with elevated UOM and evidence of burning. Coexistence of testate taxa from opposite ends of the hydrological gradient such as *Arcella discoides* and *Hyalosphenia subflava* has previously been linked with high bulk density (Charman *et al.* 2006, Booth 2008) and unusually high inter-annual variability in water table depth. Despite revegetation after fire damage *Arcella discoides* persists but a reduction of *Hyalosphenia subflava* and increasing *Archella flavum* provides evidence of a ‘pooling’ environment as shown by the prevalence of *Sphagnum s. Cuspidata*. Hydrological characteristics of the peat are likely to be heavily influenced by the previous damage. Changes in testate amoebae reflecting a change to more elevated water tables, as evident in the reconstructed DTWT, are listed in Table 2.

Humification

Decomposition increases steadily with depth. However, once detrended the record displays periods of low decomposition coherent with high percentages of *Sphagnum* and peaks in humification reflecting periods with more UOM, ericaceous material and often monocotyledons (Figure 5). Changes towards lower humification are listed in Table 2.

DISCUSSION

Finding robust climate proxy signals

All the palaeohydrological reconstruction techniques used in this study require careful cross-examination because proxy signals can be influenced by other factors (Blundell & Barber 2005). Macrofossils and testate amoebae can be subject to differential preservation (Johnson & Damman 1991, Wilmschurst *et al.* 2003, Swindles & Roe 2007, Swindles *et al.* 2020) and can be hydrologically complacent due to dominating eurytopic taxa. Some concerns exist regarding the transfer functions employed for reconstructing water table levels based on testate amoebae including spatial autocorrelation (Telford & Birks 2009), uneven sampling of the environmental gradient (Telford & Birks 2011) and the use of clustered datasets (Payne *et al.* 2012). Humification records have also come under scrutiny because

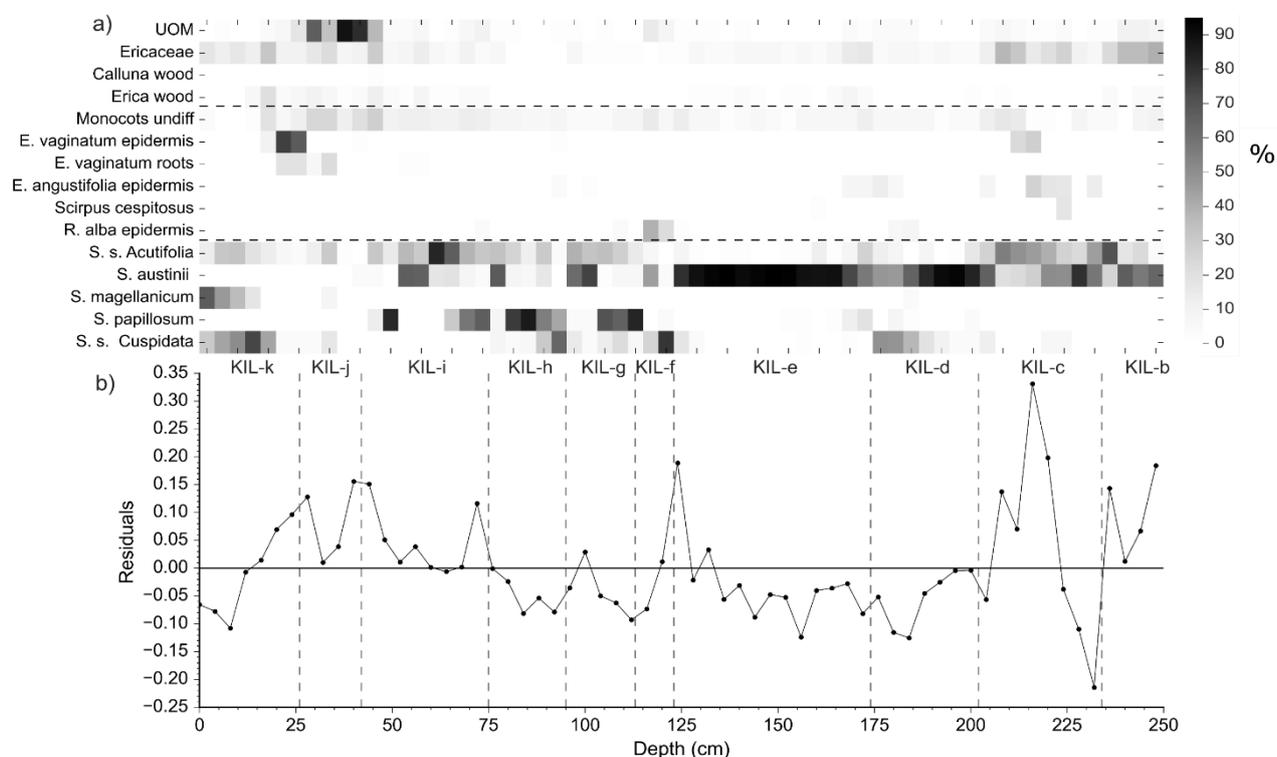


Figure 5. Heatmap of plant macrofossil percentage abundance (a) and detrended humification (b) for Killorn Moss with zones from the macrofossil record displayed.

observed variation can reflect differential decay of vegetation types and not necessarily changes in the environmental conditions controlling decay (Coulson & Butterfield 1978, Caseldine *et al.* 2000, Yeloff & Mauquoy 2006, Hughes *et al.* 2012). Signal overwriting and temporal lags due to secondary decomposition are also possible (Morris *et al.* 2015). The commonly used extraction/measuring technique for peat humification (Blackford & Chambers 1993) has been questioned as poor correlation was found between the UV-ABS of alkali extractions and results delivered by other techniques used to examine peat decomposition such as Pyrolysis GC-MS, C/N, FTIR band intensities and $\delta^{13}\text{C}$ (Biester *et al.* 2014). However, by critical examination of each of several proxy records, a more robust signal regarding changes in water table depth may be obtained than from one proxy alone. Changes in water table depth in raised bogs are predominantly attributed to the allogenic factor of the precipitation/evaporation balance and therefore climate (Barber 1981) and it has been argued more specifically in terms of changes in summer moisture deficit predominantly due to changes in precipitation (Charman *et al.* 2009). However, especially in the last few centuries, human activities such as artificial drainage, burning, peat cutting and atmospheric pollution can lead to changes in hydrology irrespective of climate. Work by Morris *et al.* (2015) and Waddington *et al.* (2015) has reaffirmed the potential importance of autogenic factors on the signal, and observed differences

between multiple cores from a site (Blaauw & Mauquoy 2012) have demonstrated the existence of internal noise of likely autogenic origin. Climate is undoubtedly of utmost importance but the signal can be mixed with noise and responses can be non-linear (Swindles *et al.* 2012) which is why comparison of the signal with another record from the site itself, or from neighbouring sites or sites in the same region, can permit coherent changes to be identified and regarded as forced by climate.

Proxy comparisons

Reduced levels of humification often coincide with higher abundances of *Sphagnum* with little evidence to indicate any differences between *Sphagnum* taxa (Figures 3, 5 and 6). Elevated levels of humification are present at times of high UOM or Ericaceae and are related primarily to lower water tables or alternatively high UOM resulting from damage such as burning as seen in KIL-j. Interestingly, increases in UOM and humification, although appearing to predate drying of the surface in KIL-j as indicated by increases in *Hyalosphenia subflava*, reflect the action of fire burning into the peat record from above leaving the testate record relatively unaffected. The synchronous post fire resurgence of *Eriophorum vaginatum* and increase in *Hyalosphenia subflava* confirm this. Minor peaks exist in periods dominated by *Sphagnum* at 100 cm and 72 cm and, although these appear to be due to small increases in monocots or UOM providing a non-linear increase in

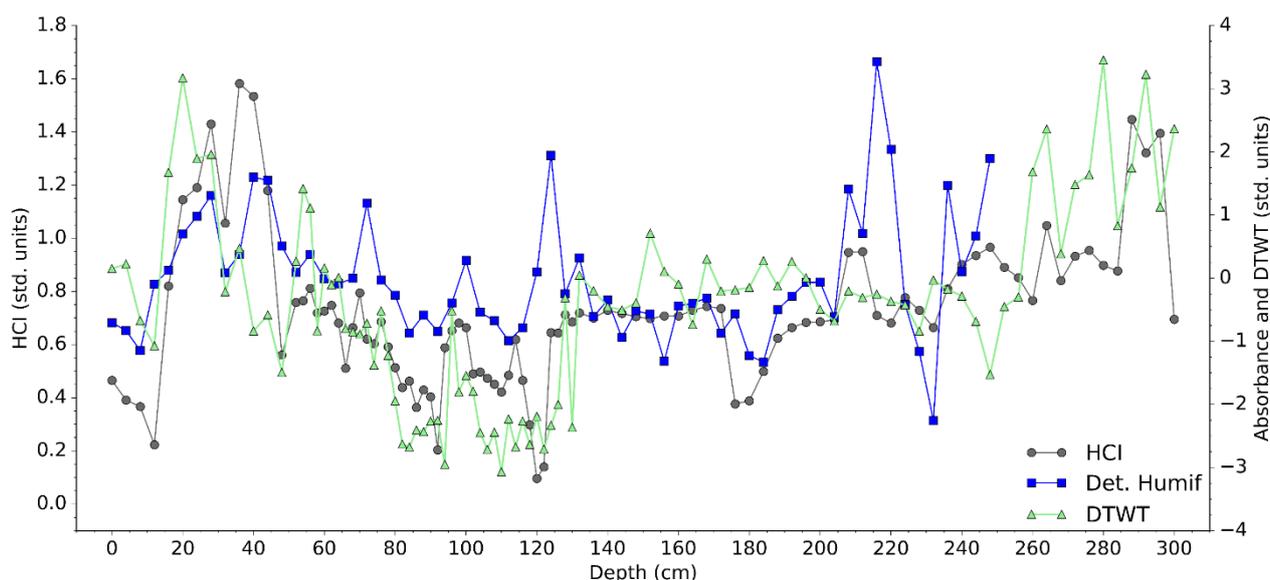


Figure 6. All proxies vs depth from Killorn Moss. Grey line and circles, blue line and squares and green line with triangles represent macrofossil HCI, humification absorbance and Depth To Water Table (DTWT) respectively. All are in standardised units.

humification, testate amoebae DTWT reconstructions do show preceding increases in DTWT. High levels of humification peaking at 124 cm and 208–220 cm are not synchronous with high HCI and therefore potentially drier conditions as indicated by the macrofossils. However, humification levels had consistently risen from 140 cm peaking at 124 cm coherent with increased but relatively minor levels of UOM and the soil fungus *Cenococum* sp. which is indicative of dry aerated conditions (Ferdinandson & Winge 1929). The dominant macrofossil here is that of *Sphagnum austinii* Sull. ex Aust. (formerly *S. austinii* Hornsch. Ex Russ.) which is a relatively eurytopic species with regard to water table depth. Elevated humification at 216–220 cm is coincident with increased abundance of *Eriophorum angustifolium*, the leaves of which have been noted as being especially susceptible to decay (Hughes *et al.* 2012). This species, although generally indicative of wet conditions but not supported by the testate amoeba data here, may be providing a skew to the humification due to its ease of decomposition.

Changes in the DTWT record reconstructed from testate amoebae are largely coherent with those in the HCI index (Figure 6) with a few exceptions, although apparent magnitudes of the changes observed can be dissimilar. Substantial difference in inference from the records is evident at 256–240 and 204–176 cm. In the former case a peak in *Amphitrema wrightianum* tests indicating wet conditions occurs in a section largely dominated by the eurytopic macrofossil *Sphagnum austinii*. In the latter a substantial colonisation of *Sphagnum* s. *Cuspidata*, indicating a change to wetter conditions, is evident but is not supported by the testate amoeba record as *Diffflugia pulex*, which is relatively ill-defined with regard to the water table with few instances in the transfer function employed (Charman *et al.* 2007), dominates. This example highlights the reduced insight when using a single proxy in isolation. Changes that are coherent between the two proxies do occasionally display a lag, with the testates displaying the change before the plant macrofossils, as may be expected. The multiple proxies employed in this study mean that such issues with an individual proxy can be identified and interrogated leading to a more robust set of inferences about changes in water table and ultimately climate. Ten changes to higher water tables (Figure 7) are shown by at least two of the three proxies (Table 2).

Comparison of Killorn Moss and Shrigarton Moss

Replicated changes in records from the same region or from multiple cores from a site would suggest that an overriding allogenic factor such as climate is the

cause. A single core was employed at Killorn Moss after stratigraphic surveying was carried out. However, comparison can be made with a previous study (Langdon 1999, Langdon & Barber 2005) carried out at the neighbouring site Shrigarton Moss (Figure 1) as well as other sites in the region and beyond. Although not originally designed to be part of this study it does provide a fortuitous opportunity for comparison. The original analyses at Shrigarton predate those at Killorn and therefore the analyses have been reprocessed to aid comparability. The original dates (Langdon & Barber 2005) have been employed to create a new age-depth model using Bacon (Blaauw & Christen 2011). New reconstructed DTWTs from the original testate amoebae data have been produced based on the ACCROTELM function (Charman *et al.* 2007). A new Hydroclimatic Index (HCI) using the original macrofossil data (Langdon & Barber 2005) has also been calculated. Changes to wetter conditions observed by at least two proxies are evident from ca. 860 BCE MAR 1011–791 BCE, ca. 610 BCE MAR 748–494 BCE, 130 BCE MAR 234 BCE–1 BCE, 350 CE MAR 111–639 CE, 860 CE MAR 575–1082 CE and 1160 CE MAR 970–1258 CE (Figure 7). All of these six changes to wetter conditions at Shrigarton Moss share error ranges with events observed at Killorn Moss. Of the ten events registered at Killorn, two have no or little crossover with dating errors at Shrigarton Moss. Sampling frequency is higher for much of the record at Killorn Moss so a greater number of changes may be expected or changes should at least be better defined. More robust comparison would require further dating and would be aided by tephra isochrones. The Glen Garry tephra (Barber *et al.* 2008) was found by Langdon at Shrigarton Moss (Langdon & Barber 2005) but was not evident at Killorn Moss despite their proximity. However, the four events highlighted in Figure 7c are clearly registered at both locations with estimated age differences within ± 50 years.

The palaeoenvironmental record at Killorn Moss

Clear evidence exists for a substantial increase in wetness in the early 1st millennium BCE at both Killorn and Shrigarton Mosses although the increase is ‘staggered’ across several centuries at Killorn with peak wetness evident in the mid-1st millennium BCE at both sites (Figure 7). The ‘staggered’ increase in water table is displayed elsewhere in peatland archives in Scotland at Temple Hill Moss (Langdon *et al.* 2003), in northern Britain (Charman *et al.* 2006) and in Ireland (Swindles *et al.* 2013). Substantial evidence of global climate deterioration ca. 850–650 BCE (Wanner *et al.* 2011) exists and is clear in peatland archives especially in NW Europe (van Geel *et al.* 1996, Blundell & Barber 2005, Borgmark 2005,

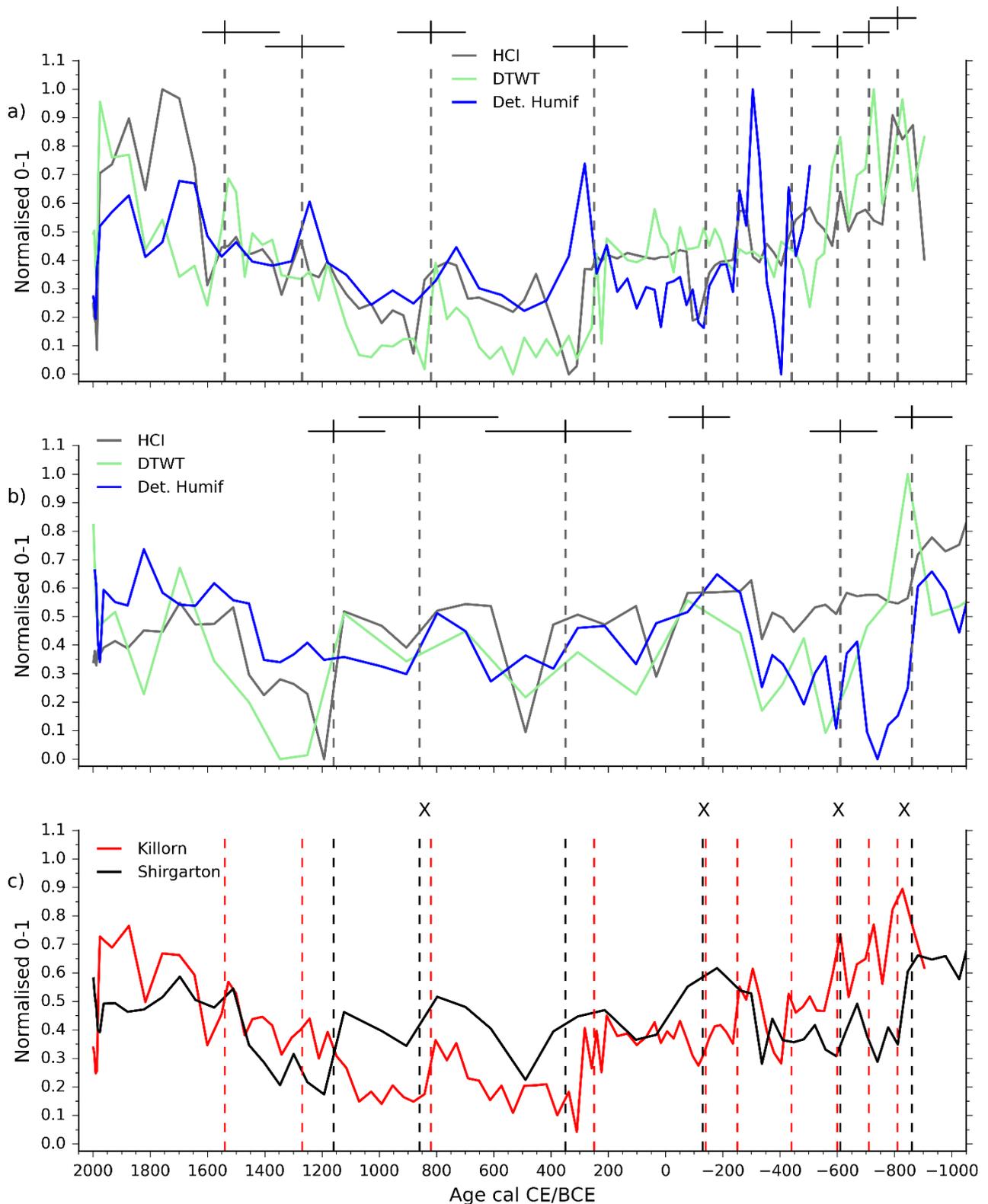


Figure 7. Comparison of normalised proxy data (HCI - grey, DTWT - green, detrended humification - blue) versus age CE/BCE together with highlighted wet shifts (grey dashed vertical lines) for a) Killorn Moss, b) Shrigarton Moss and c) the mean of proxy data from Killorn (red) and Shrigarton (black) and the respective wet shifts from both in corresponding-coloured vertical dashed lines. Modelled ages and age ranges for each shift are shown above the plots in a and b with the small vertical lines representing the median of the age range. Proxies are normalised between 0-1. Wet shifts within 50 years of each other between the two sites are highlighted with crosses.

Charman *et al.* 2006, Plunkett 2006, Swindles *et al.* 2012, Swindles *et al.* 2013), North America (Booth & Jackson 2002, Hughes *et al.* 2006, Nichols & Huang 2012, Blundell *et al.* 2018), South America (Chambers *et al.* 2007) and China (Lui *et al.* 2017), as well as in records of European lake level (Magny 2004) and archives of glacier advance (Holzhauser *et al.* 2005, Solomina *et al.* 2015). Substantial changes in solar activity (van Geel *et al.* 1999, Chambers *et al.* 2007), reduced ocean circulation strength in the North Atlantic (Bianchi & McCave 1999, Bond *et al.* 2001, Oppo *et al.* 2003) and changes in atmospheric circulation (O'Brien *et al.* 1995) have been detected and proposed as possible forcing mechanisms resulting in increased wetness at this time.

Successive increases in wetness indicated at Killorn Moss ca. 250 BCE and ca. 140 BCE, marked by greater abundance of *Sphagnum s. Cuspidata* and reduced humification, are coherent with changes displayed in peatland records elsewhere within northern Britain and Ireland (Barber *et al.* 1994, Chambers *et al.* 1997, Charman *et al.* 1999, Mauquoy & Barber 1999, Ellis & Tallis 2000, Barber *et al.* 2003, Blundell & Barber 2005) and NW Europe (Aaby 1976, Nilssen & Vorren 1991). Farther south, in the north of England, a phase of extensive gullying was reported at the Howgill Fells between ca. 250 BCE and 150 CE, related in part to elevated summer wetness as evidenced from a nearby peatland palaeoclimate record at Archer Moss (Chiverrell *et al.* 2008). Evidence also exists for change farther afield with glacier advances ca. 750 BCE in Scandinavia (Karlen 1988, Wanner *et al.* 2000, Solomina *et al.* 2015) peaking ca. 350 BCE ka, coincident with increases in European lake levels (Magny & Richoz 1998). Despite a substantial change from *Sphagnum austinii* to *Sphagnum s. Cuspidatum* and *E. angustifolium*, accompanied by a reduction in humification, this change at Killorn is not replicated by the reconstructed DTWT which displays little change from the previous zone dominated by *Sphagnum austinii* other than a small increase in *Diffugia pulex*. This discrepancy highlights the potential complacency in the testate amoebae record when dominated by *Diffugia pulex* and the advantage of having multiproxy data to resolve it.

Change to a wetter climate around the transition from the Romano-British period into the Dark Ages is commonly reported based on evidence from peatland palaeoclimate records across the UK and Ireland (Blackford & Chambers 1991, Ellis & Tallis 2000, Langdon *et al.* 2003, Swindles *et al.* 2013)

ca. 550 CE and is often linked to increased solar activity. However, this prominent event is not recorded at Killorn Moss at that time. A minor increase in DTWT and decrease in HCI is evident ca. 480 CE at Killorn, but in the context of the entire record it is relatively minor. A substantial change to wetter conditions is recorded earlier, ca. 250 CE, by all three proxies together with a subsequent halving of the accumulation rate. At least from the perspective of reconstructed DTWT it is possible that the peatland, having switched to a wetter system post ca. 250 CE and already exhibiting high levels of *Amphitrema wrightianum* as a consequence, would have little scope remaining to record any additional increase in wetness. At neighbouring Shirlarton Moss deterioration is evident ca. 350 CE as indicated by an increase in *Sphagnum s. Cuspidata* and a lowering of absorbance. Although not reported as such in the original publication (Langdon & Barber 2005) it is evident here post reprocessing of the age-depth relationship. Evidence from other peatland climate records does show an apparent earlier shift within the Romano-British Period similar to that seen at Killorn and, encouragingly, many of these records demonstrate both (Aaby 1976, Wimble 1986, Nilssen & Vorren 1991, Mauquoy & Barber 1999, Hughes *et al.* 2000, Chiverrell 2001, Barber *et al.* 2003). It may be that these are two separate defined events or at least are two prominent stages of a progression to wetter conditions towards the end of the Romano-British period. Charman *et al.* (2006) report a clear Dark Age deterioration signal ca. 500 CE in the compiled record for northern England but a much more diluted presence in the compiled peatland records farther north in the UK and attributes it to the degree prevailing westerlies may have migrated northward.

Peat palaeoclimate archives often record a further shift to wetter conditions after brief amelioration following the commonly noted 'Dark Age', and before amelioration towards a period coincident with the commonly termed 'Medieval Warm Period'. Increased wetness at Killorn is indicated by all proxies ca. 820 CE. However, the timing for change is far from synchronous between sites regionally, with an event distinct from the 'Dark Age' deterioration often reported starting in the UK sometime ca. 650–950 CE (Charman *et al.* 1999, Mauquoy & Barber 1999, Chiverrell 2001, Mauquoy & Barber 2002, Blundell & Barber 2005) and in NW Europe (Svensson 1988, Nilssen & Vorren 1991). Evidence from Bolton Fell Moss (northern England) and Mongan Bog (Ireland) points to deterioration ca.

850 CE (Barber *et al.* 2003), while a compilation of selected records from northern Britain (Charman *et al.* 2006) led to a reported change ca. 690 CE and compilation of two records from Ireland (Blundell *et al.* 2008) indicated a change at ca. 805 CE. A later compilation including these and many more primarily bog-based records from Ireland (Swindles *et al.* 2013) showed that, after such a time interval post record compilation, any event is either dwarfed by the preceding deterioration from a ‘Roman Warm Period’ or diluted by the compilation process. However, tree ring archives demonstrate reduced ring widths for several decades ca. 800 CE which can be interpreted to represent reduced summer temperatures (Briffa *et al.* 1990, 1992; Grudd *et al.* 2002) in NW Europe and beyond (Lamarche 1974), pointing to a period of reduced evapotranspiration and potential for elevated water tables in peatlands. Glacier advances in Europe were also recorded around this time (Karlen 1988), albeit with relatively weak glacier advances in central Europe (Holzhauser *et al.* 2005).

Evidence for deepening of the water table post ca. 1130–1530 CE, most prominently in the testate amoebae derived DTWT and therefore drier conditions, is punctuated briefly by a more minor deterioration ca. 1270 CE as evidenced by humification and macrofossil evidence and ended by deterioration ca. 1540 CE. Similarly timed double deteriorations post Medieval times were noted in the early record developed by Barber (1981) at Bolton Fell Moss in northern England and elsewhere across the UK (Langdon & Barber 2005, Charman *et al.* 2006, Blundell *et al.* 2008, Swindles *et al.* 2013). It is clear however that dating error and differences in sampling resolution resulting in large variations in time between samples contribute to a variety of reported dates, although often within the error ranges reported for Killorn Moss. This is especially problematic when separate deteriorations are evident across a short timeframe. Changes in the second half of the last millennium are often linked with variations in solar activity (Jiang *et al.* 2005, Mauquoy *et al.* 2008, Nichols & Huang 2012). Although deterioration at ca. 1270 CE is centred on the transition to the Wolf Minimum, the later change at Killorn did not happen as solar activity increased after the Spörer Minimum. However, testate derived water table reconstruction (less affected by recent fire damage) does show a period of wetter conditions ca. 1540–1730 CE which encompasses the Maunder Minimum and the mid to late 17th century, associated with reduced seasonal temperatures from the Central England temperature records and documentary-based compilations from Europe (Alexandre 1976a, 1976b; Pfister 1981).

CONCLUSIONS

- At Killorn Moss a multiproxy approach has resulted in a robust and well supported record of changes in wetness of the site for the last 3000 years.
- Changes to wetter conditions supported by at least two proxies are evident at Killorn ca. 810–770 BCE, 710 BCE, ca. 600 BCE, ca. 440 BCE, ca. 250 BCE, ca. 140 BCE, ca. 250 CE, ca. 820 CE, ca. 1300 CE and ca. 1540 CE.
- Although largely complementary, all three of the individual records have deficiencies that have been able to be informed by the remaining proxies employed. Cross examination has permitted detection of deteriorations despite periodic dominance of the eurytopic species *Sphagnum austinii* and complacency in the testate amoebae record especially when dominated by *Diffflugia pulex*. A multiproxy approach has also partially overcome the detrimental effect of fire from recent anthropogenic burning of the upper 45 cm of the record. Despite destroying macrofossil and humification records the testate amoebae record remained relatively unaffected.
- The more quantitative transfer function output derived from testate amoebae and perceived comparative lack of associated complications of interpretation have led to more recent studies and compilations concentrating on transfer function data alone. Although understandable it should not be thought that the two remaining proxies (macrofossil and humification data) lack merit and within this study they provide valuable insights.
- Comparison has been made with a neighbouring record 2 km away at Shirlarton Moss, where many changes reflect those at Killorn Moss within dating errors. However, substantial dating error envelopes prevent definitive clarity over the similarity of records. Comparison with peat-based and other archives in UK and north-western Europe imply similarities of events associated with conditions conducive to more elevated water tables such as reduced summer temperature or increased wetness. However, the greatest barrier within peatland palaeoecology/palaeoclimatology is still reconciling events between locations whilst contending with substantial dating errors.



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AUTHOR CONTRIBUTIONS

ACB carried out fieldwork, undertook laboratory work and wrote the first draft of the manuscript. PL contributed data and helped to rewrite drafts.

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