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Abstract

A dendrochronological investigation was undertaken on subfossil Scots pine (*Pinus sylvestris* L.) stumps following their discovered during conservation management activities at Wem Moss, a small (28ha) former raised mire in Shropshire, UK. Two ring-width chronologies were constructed from 14 of the 17 trees investigated spanning 198 and 208 years respectively. Whilst absolute dating was not possible, radiocarbon assays provided an estimated age for this mire-rooting woodland of between 3015 – 2505 years Cal BC, coinciding with the age traditionally associated with the widespread mortality of pine trees throughout much of the UK and Ireland, The Pine Decline (circa 4 ka radiocarbon years BP). Placed in a wider geographical context, the Wem Moss pines are located within the wider lowland area of the Meres and Mosses Region, where previous studies on subfossil pine have demonstrated protracted declines in mire-rooting trees. These have included tree mortality significantly post-dating The Pine Decline, notably at larger peatland sites exceeding 5.5 km^2. This macrofossil evidence for the presence of Scots pine into the late Holocene is supported by continuous *Pinus* pollen representation at peatland sites in the Welsh Marches (English-Welsh border) suggesting the possible survival of native Scots pine trees in this area up to the present-day. This research highlights the incomplete and patchy nature of palaeo-vegetational records and also the potential for genetic research on living Scots pine in possible refugial areas in the UK and Ireland.

Key Words

Anaerobic Preservation, Dendrochronology, Peatland Archives, Pine Decline; *Pinus sylvestris* L.; Radiocarbon (^{14}C) Dating

1. Introduction

Under natural environmental and climatic conditions many tree species are capable of colonising peatlands, particularly during periods of dry or relatively-dry surface conditions [1,2]. Research in the last decade has demonstrated that tree growth and survival in these often-extreme environments is predominantly regulated by hydrological conditions, with climatic parameters correlated less-well with dendrochronological records [2-5]. Peatland drainage events in the twentieth century CE have been clearly shown to promote tree colonisation and tree growth [6-9].

Past tree growth on peatlands has been demonstrated over many centuries, with isolated tree stumps and fallen trunks or apparent forest 'layers' revealed by erosion events, peat cutting, drainage and other human-related activities in the UK, Ireland and further-a-field [e.g. 2,10-16]. Whilst these trees are thought to represent previous drier peat surfaces, their preservational state can indicate wet conditions immediately post-mortem (intact bark and vertical trunk components) or relatively dry conditions (little trunk component remaining), as observed in subfossil pine (Figure 1), supporting other evidence for rapid natural fluctuations in past mire surface hydrology during the Holocene.

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Preservation of organic remains in waterlogged peatlands is exemplified by investigations of bog bodies, such as Tollund Man (Denmark) and Lindow Man (England), that have provided detailed insights in to our prehistoric past [17]. Such finds can also demonstrate imperfect preservation, with for instance bone demineralisation in acidic ombrotrophic peats and bone survival in nutrient-rich fens [18]. A variety of subfossil tree species have been found in peat ranging from birch (Betula spp.), pine (*P. sylvestris*), oak (Quercus spp.), alder (*Alnus glutinosa*), willow (Salix spp.), hawthorn (Crataegus spp.) and hazel (*Corylus avellana*) in southern Pennine blanket peats, northern England, UK [11,19] to yew stumps (*Taxus baccata*) in the fenlands of eastern England [20]. Preservation and utility of these trees for palaeoecological investigations can however vary considerably, with for instance, the frequently occurring macrofossils of alder (*Alnus glutinosa*) & birch (Betula spp) failing to provide robust samples with sufficient tree-ring series for dendrochronological investigation. By contrast oak (Quercus spp.) and pine (*Pinus sylvestris*), due to their generally broad spatial and temporal occurrence, and comparatively better preservation, have been the focus of palaeoecological investigations since the 1960s CE [2,21-28].

***Figure 1.** Subfossil bog pine (P. sylvestris) at Lindow Moss, Cheshire, UK. A) Ex situ small diameter tree removed from an upper 'regeneration layer' in ombrotrophic peat – note c 20cm of vertical trunk component facilitating sampling for dendrochronology. B) In situ stump demonstrating some damage caused during mechanised peat extraction, but also limited surviving trunk component. Scale length 23cm.*

Research utilising subfossil trees and other proxy records such as pollen has revealed natural developments in wetland sites progressing from open water to eutrophic fens, culminating in raised ombrotrophic bogs [29]. Whilst this hydroseral succession has been demonstrated at numerous sites throughout north-west Europe the successional pathways for wetland environments are known to be more complex [30], and some regions such as the Lancashire Coastal Plan are thought to have remained at early successional stages for millennia, promoting the persistence of extensive and unique bog oak woodlands [16,31-33] (Figure 2). Dendrochronological dating of bog oak and bog pine woodlands, notably in Germany and Poland, has revealed extensive tree colonisation of European bogs correlating with periods of climatic amelioration (e.g. Holocene Thermal Maximum), as well as mass mortality events associated with climatic deterioration. The latter has demonstrated synchronous climatic forcing throughout north-western Europe, particularly during the mid-Holocene [2,15,27,34,35].

Figure 2. Contrasting preservational environments for subfossil bog pine in north-west England: a) Lindow Moss, a former raised peat bog, north Cheshire (image: 6th June 2012) b) a low-lying field (5-10 m asl) adjacent to Curlew Lane, south-west of Rufford on the Lancashire Coastal Plain. Inland hills (near Parbold) approximately 6 km to the south-east can be seen in the distance (image: 16th October 2019).

A significant concentration of radiocarbon age determinations for *P. sylvestris* microfossils (sharply declining pine pollen representation in pollen diagrams) and widespread occurrence of macrofossils (tree trunks and stumps) from the UK and Ireland has previously been noted at around 4000 ^{14}C years BP and has been termed the 'Pine-decline' [36, pp. 145-146]. Although the precise mechanisms involved in this apparent 'event' were initially a matter of conjecture, climatic deterioration was suspected, and also corroborated by existing evidence from other proxy records such as lake sediments and peat stratigraphy [37-40 cited by 36]. The 'Pine Decline' has remained contested within palaeoecology, attributed to climate change, competition between coniferous and broadleaf tree species, humans, pathogens and even the potential impacts of Icelandic volcanism. The latter, for instance, has included heated debates relating to the application of dating techniques and palynological criteria for the presence of local woodland [41-47].

This research presents new palaeoecological data relating to a subfossil pine woodland from a former raised bog from the border between Wales and England (UK). It examines the significance of macrofossil records from the Meres and Mosses region, including Wem Moss, in relation to the 'Pine Decline' and to palaeoecological and palaeoclimatic records further-a-field. It also highlights potential shortfalls demonstrated in reliance on spatially disparate preservational environments.

2. Study Area and Site

Wetlands and former wetlands within the UK counties of Cheshire, Staffordshire and Shropshire are collectively known today as The Meres and Mosses Region, an area of predominantly low-lying topography sharing not only similar landscape characteristics, but also similarities in glacial, landscape, vegetation and human history [48-50]. These wetlands and their environmental archives have been the focus of a considerable volume of both ecological and palaeoecological research including seminal works on the terrestrialisation of wetland sites, development of *Schwingmoor* and the definition of palynological 'events' such as the *'Tilia Decline'* [e.g. 51-55]. The research reported here formed part of a project that highlighted the nature and value of the wetland archives in this region and included both detailed palynological investigations, as well as the analyses of subfossil pine trees excavated at Wem Moss [56,57].

Figure 3. *Recovering subfossil bog pine trees from Wem Moss, Shropshire in March 2015. A) Sampling tree discs using a chainsaw from well-preserved stumps close to the tree root crowns. Note corrugated plastic barrier inserted into the peat – left of image. B) 17 pine disc samples prior to transportation to the Dendrochronology laboratory at Manchester Metropolitan University.*

Wem Moss is a small (28 ha), lowland raised bog in Shropshire, UK (National Grid Reference SJ 473 343) and forms part of a larger conservation area, Fenn's, Whixall and Bettisfield Mosses National Nature Reserve and is noted for raft spiders, the Large Heath Butterfly (*Coenonympha tullia*) and the common European Viper or Adder (*Vipera berus*). It is owned and managed by the Shropshire Wildlife Trust [58] (Natural England 2008). In 2015 conservation management required the insertion of a linear hydrological barrier to further site re-wetting, and necessitated the removal of a considerable number of subfossil bog pine trees (*Pinus sylvestris* L.) from within the peat. Following a request from the Shropshire Wildlife Trust to ascertain the age of these trees, disc samples were removed from 17 subfossil stumps for dendrochronological analyses (Figures 3a & 3b).

3. Materials and Methods

3.1 Dendrochronology

Disc samples were allowed to air dry and then polished using progressively finer grades of sandpaper and a belt sander to make the wood structure and tree-ring patterns fully visible for measurement. A mean ring-width record was then created for each of the 17 disc samples using dendrochronological equipment and software routines described in Tyers [59] and Lageard et al [25]. A detailed description of the methodology followed in this research, and also recommended for the dendrochronology of subfossil pine, including cross-matching procedures and chronology-building, is described in detail elsewhere [16].

3.2 Radiocarbon dating

Following the creation of floating site ring-width chronologies, samples of wood were carefully removed from discs using a hammer and narrow-bladed chisel (avoiding any potential contamination from modern or older carbon) representing the youngest chronology components e.g. rings 191-198 from disc Wem 01 from chronology Wem 2_2 (exceeding the minimum weight 3-100 mg required for AMS dating). Samples were sealed in laboratory sample bags and sent to Beta Analytic (Miami, USA) for ^{14}C assay. All ^{14}C date calibrations including for the Wem Moss wood samples utilised the IntCal20 atmospheric curve [60], and previously published ^{14}C dates included in the discussion were recalibrated using OxCal v. 4.4 [61].

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4. Results

Dendrochronology

Ring-width measurements of the disc samples were undertaken in the Dendrochronology Laboratory at Manchester Metropolitan University, revealing ring counts of 49-269 years. Subsequent cross-matching demonstrated contemporaneity between 9 of the 17 mean ring-width series, enabling the formation of two site chronologies, Wem 2_2 and Wem 4_1 (see Figures 4 & 5).

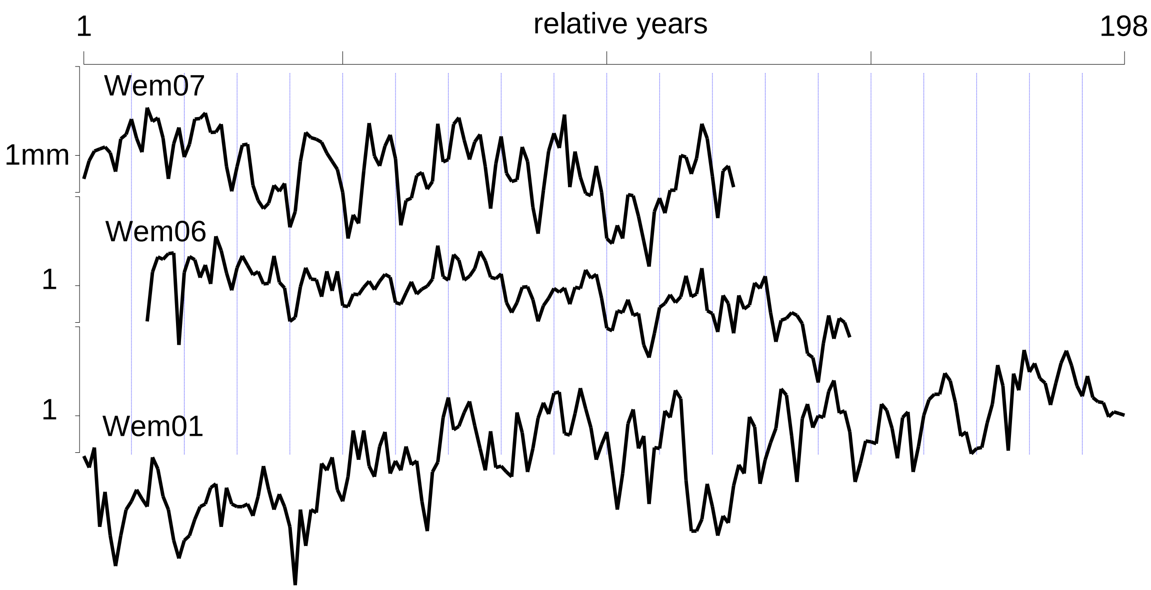

***Figure 4.** Contemporaneity and variability in subfossil pine growth from the same peat bog: P. sylvestris ring-width records Wem 01, Wem 06 & Wem 07, components of the 198 year site chronology Wem 2_2.*

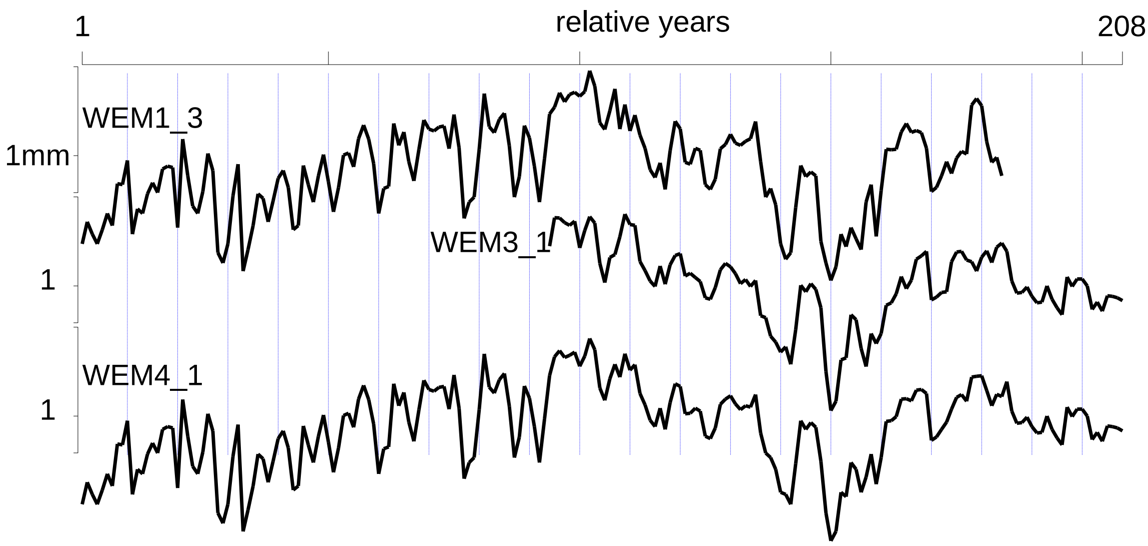

***Figure 5.** Ring-width records of interim site chronologies WEM 1_3 (3 ring-width records) and WEM 3_1 (2 records) and the final 208 year site chronology Wem 4_1 (6 records) illustrating the chronology building process.*

As cross-matching with other available regional subfossil pine reference chronologies was unsuccessful, age-estimation for samples from the two site chronologies (WEM 2_2 and WEM 4_1) was reliant on the results of the radiocarbon age determination.

Chronology	Tree	Chronology years	Radiocarbon age	Calibrated age range (2 sigma)
Wem 2_2	WEM01	191-198	4330 +/- 30 BP (Beta – 424347)	3015 to 2895 Cal BC
Wem 4_1	WEM10	199-208	4100 +/- 30 BP (Beta – 424348)	2860 to 2505 Cal BC

Table 1. *Radiocarbon dates associated with samples from chronologies Wem 2_2 and Wem 4_1*

Radiocarbon Dating

Youngest series of tree-rings were removed from subfossil pine disc samples emanating from both site chronologies (wood immediately proximate to tree bark: Wem 2_2 rings 191-198; Wem 4_1 rings 199-208) and sent for radiocarbon dating. Calibration (2 sigma) of the resultant ^{14}C dates suggest that the dendrochronological records are closely-related and may emanate from the same continuum of mire-rooting woodland centred on the period 3015 – 2505 Cal BC (see Table 1).

5. Discussion

The close proximity of the radiocarbon dates for the two floating pine ring-width chronologies from Wem Moss suggests that the trees sampled in this research comprised part of the same mire-rooting woodland probably extant for several centuries leading up to their mortality at or leading up to 4 ka BP, 'typical' pine macrofossil evidence of the 'Pine Decline' [36]. More detailed investigations of similar subfossil woodland elsewhere in wider the Meres and Mosses Region have however revealed a more complex pictures of subfossil pine woodland decline with distinct temporal phases. At White Moss (45 km to the north-west in south Cheshire) three phases of macrofossils were identified. White Moss Phase B was initially assayed by radiocarbon, but subsequently dated precisely by dendrochronology to 2881-2559 BC [25,62,63]. The youngest tree layer/s from White Moss (Phase C) comprised an upper 'regeneration' layer(s) of small diameter stumps thought to represent the last attempts of woodland to re-establish in an increasingly wet environment, unsuited to tree growth (2484–2199 Cal BC & 1972-1740 Cal BC) [25]. A similar 'regeneration' layer is currently under investigation at Lindow Moss (north Cheshire), and the morphology of many of its components provide further evidence implicating mire hydrology in tree mortality after 2569-2146 Cal BC [16,64] (see Figure 6).

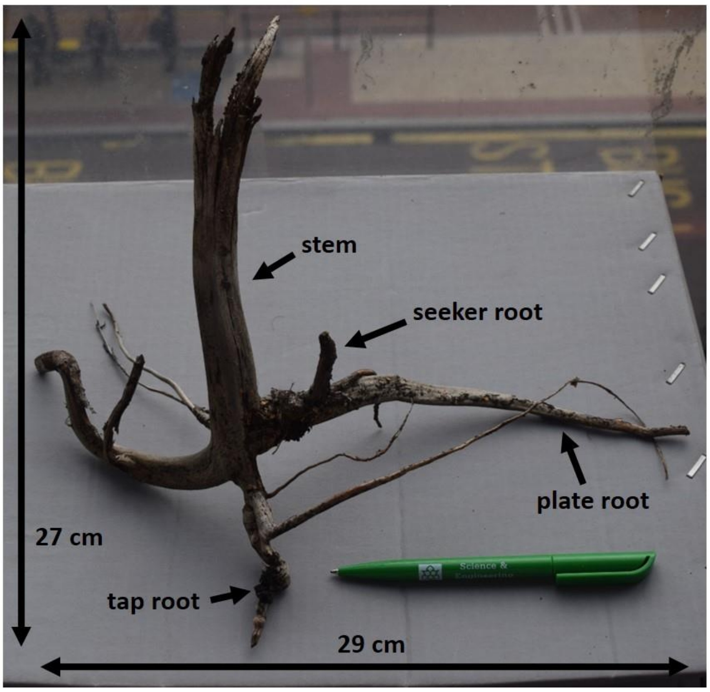

Figure 6. *A small-diameter subfossil pine tree (P. sylvestris) recovered from the uppermost layers of peat containing bog pine woodland at Lindow Moss, Cheshire (stem top broken by machinery during mechanised peat extraction). Note the presence of seeker roots, a likely response to prolonged waterlogging.*

Dendrochronologically-dated phases of mire-rooting pine woodland during the Holocene in the UK and Ireland are rare [25,63,65,66], and contrast with temporally and geographically more extensive European records whose dating has benefitted from the widespread contemporaneity of bog oak and bog pine woodlands [2,15,34,35]. It is however possible to compare the radiocarbon dates for the Wem Moss subfossil pine woodland to investigations of subfossil pine from the immediate and wider geographical region in the UK (Table 2 & Figure 7). Previously-dated pine and oak macrofossils and microfossil (pine pollen) events from peatlands in Shropshire are listed in Table 2 and reveal a series of radiocarbon age-estimates post-dating the age traditionally associated with the 'Pine Decline' (4 ka BP). These local investigations focussed primarily on a layer of pine stumps originally described by Hardy [67] at Whixall Moss (part of the larger Fenn's and Whixall Mosses peatland complex covering over 550 ha).

Hardy also recounted the discovery of a bronze looped palstave (axe) in AD 1927 by Mr George Saywell whilst *'digging turf'*, and *'lying on top of the roots of the old pine, about 8 ft. from the surface'* [67 p377]. Typologically this artefact dated to the Middle Bronze Age archaeological period, circa 1500 to 1000 years BC, and the find spot was also proximate to an earlier discovery (AD 1889) of a human 'bog body' [68]. The axe find in particular, provides intriguing evidence of human presence contemporary with the bog pine woodland, although to this author's knowledge no direct human impacts, such as axe marks, have ever been found on pine macrofossils either here or further-a-field (UK / elsewhere).

Hardy's pine stump layer was initially dated to 2307+-110 (761-106 Cal BC), although the specific nature of the organic sample and stratigraphic information were not provided [63]. Subsequently, dendrochronological investigations were undertaken by Haslam who made ring-width measurements for 14 subfossil trees and constructed a 96-year chronology, making observations on pine stump morphology and also their proximity to an overlying *Sphagnum papillosum - Sphagnum cuspidatum* lawn community (initiating around 2180 +/- 50 BP or 397 – 3 Cal BC), and preserved as macrofossils at a peat depth of 40-44cm [69]. Further dendrochronological studies were undertaken on subfossil pine stumps revealed by peat cutting at varied locations throughout Fenn's and Whixall Mosses [13] and 6 radiocarbon assays on wood samples from dendrochronological records currently provide the best dating currently available for the Whixall Moss pine 'layer' (3140 - 2900 BP; 1508 – 932 cal BC) [70].

Publication	Site	Bog oak / Bog pine / Pine pollen	14C Age (Years BP)	Calibrated age range (2 Sigma) (Years Cal BC / AD)	Calendar date (Years BC)	Artefact dating (Years BC)	Undated tree-ring series
Hardy (1939)	Whixall Moss	Pine	-	-	-	1500 - 1000 BC	-
Turner (1964)	Whixall Moss	Pine	2307+/-110	761 - 106 Cal BC	-	-	-
Turner (1964 & 1965)	Whixall Moss	Pine pollen	c 2000	-	-	-	-
Beales (1980)	Crose Mere	Pine pollen	2310 +/- 85	753 - 164 Cal BC	-	-	-
Barber & Twigger (1987)	Fenemere	Pine pollen	1890 +/- 50	248 - 232 Cal AD	-	-	-
Haslam (1987)	Whixall Moss	Pine	2180+/-50	397 - 3 Cal BC	-	-	✓
Lageard et al (1994)	Whixall Moss	Pine	-	-	-	-	✓
Lageard & Chambers (1994)	Morris' Bridge	Oak	-	-	4596 - 4304	-	-
Grant (1995)	Whixall Moss	Pine	3140-2900	1505 - 930 Cal BC	-	-	-

Table 2. *Dating associated with subfossil Scots pine and subfossil oak macrofossils and sharp declines in Pinus pollen from Whixall Moss and other sites in Shropshire, UK. Sources: [67,69-75] Calibrations: [60,61]*

Wider Regional Context

The pollen record from White Moss (Cheshire) demonstrated that boreal woodland dominated by *P. sylvestris* was likely to have occupied significant parts of the Meres and Mosses Region between 8625+/-50 BP (SRR 3881: 7761 - 7544 Cal BC) and 5890+/-45 BP (SRR 3880: 4897 – 4616 Cal BC) [25,62]. Discoveries of pine macrofossils at Davenham (mid-Cheshire) and at Curlew Lane (Lancashire) are remnants of these early-mid Holocene woodlands, whose pre-eminence appeared to be checked shortly after 5890+/-45 BP (4897 - 4616 Cal BC) and again at 4280+/-45 (SRR 3879: 3022 - 2702 cal BC) (White Moss pollen record from core T3.75) [62] (see Figure 7).

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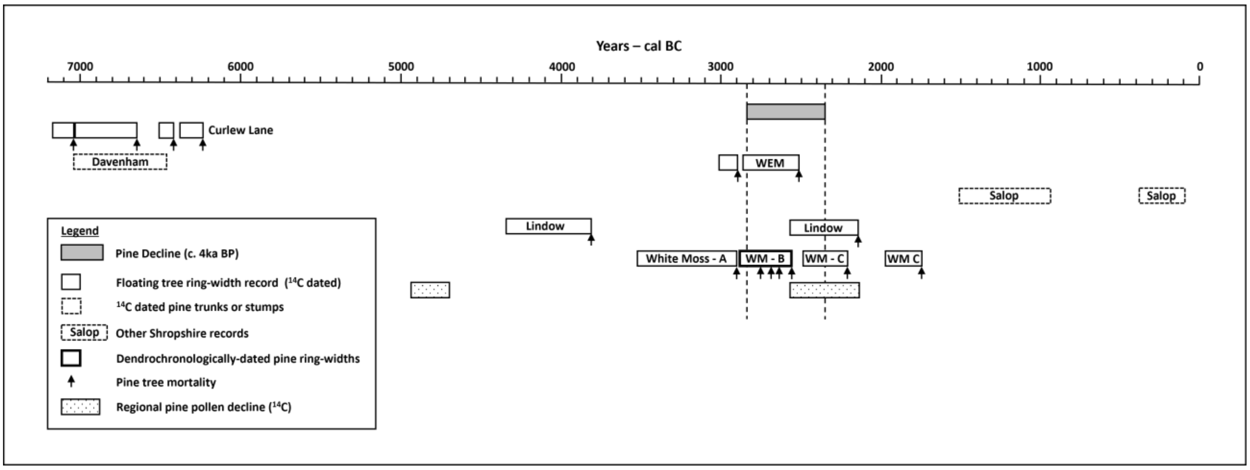

***Figure 7**. The 'classic' date often linked to the Pine Decline of 4 ka BP or 2835 - 2346 cal BC [36] and the relative dating of P. sylvestris macro and microfossils from Shropshire (Salop), Cheshire and Lancashire (Dating sources: [16,25,53,62,64,69,70,75,76 Wem Moss - this paper) ^{14}C dating at Curlew Lane, Wem, Lindow and White Mosses focussed on aging the youngest samples available; macrofossil analyses and dating were much more extensive at White Moss (4 year research project); small diameter pine stumps from upper stratigraphy at Lindow Moss (e.g. Figure 6 – currently undated), are analogous to the final regeneration layers at White Moss (WM – C). Comparisons of average ring-width indicate: wider rings and faster growth in older tree-ring series (WM – A, oldest Lindow); narrower rings and more sensitive ring-width series (WM – B, WEM, oldest Salop).*

There has been considerable debate about the often-assumed extinction of native Scots pine throughout the UK and Ireland, and this is exemplified in Shropshire. Pine pollen representation fell to background levels (c. < 1% TLP from 170cm lake core depth upwards) at Crose Mere (5.5 km SW of Wem Moss) after 2310 +/- 85 BP (763 – 164 Cal BC, Q-1233) [72], whilst at Fenemere (11.5 km SSE of Wem Moss) a similar decline occurred at 1890+/-50 BP (16 – 302 Cal AD, SRR-2920) [73]. Speculation suggested that this represented a dating discrepancy, due to pine woodland persisting on more freely draining soils or *'erroneous* [at Crose Mere] *due in-washed old carbon'* [78 cited by 69, p121]. The ^{14}C age estimate (Q-1233) however centred on a lower core depth (c 200 cm) where small quantities of pine pollen were still present [72, pp.145-145], indicating that the dates from Fenemere and Crose Mere might actually be broadly complimentary.

Precise stratigraphic comparisons of key events in the pollen record are not only compounded by the imprecision of ^{14}C dating, but also by debates surrounding the levels of pine pollen thought to be representative of local woodland. Initial criteria for the latter have varied from 20-30% total land pollen (TLP) [36,79], as pine trees are wind-pollenated and hence copious producers of pollen [80,81]. Subsequently these criteria have been progressively revised downwards, for instance with 5% TLP suggested by Bennett [82], following the discovery of pine stomata in lake sediments with contemporaneous pine pollen levels at 3-18% TLP [83]. Hall et al [42] also found < 2-3% pine pollen in peat associated with *in situ* dendrochronologically-dated pine macrofossils, questioning the wider applicability of previous research linking a pine pollen decline in northern Scotland to the effects of Icelandic volcanism [41]. The volcanic impact debate was later elaborated in a comprehensive review of the palynological evidence, although this failed to provide definitive answers [47]. A further well-replicated study from Scotland again demonstrated the presence of pine stomata in sediment from Loch an Amair and Dubh Lochan coinciding with pine pollen abundance as low as 0.4% TLP, and as a result pushing back the date for the first expansion of the native Caledonian pinewoods [84].

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Whilst *P. sylvestris* has persisted as a native tree in its Scottish heartland, despite sustained human interference [85,86], a number of recent studies have thrown doubt on its the Holocene extinction of Scots pine throughout the remainder of the UK and Ireland. Analysis of topography, pedology and vegetation in northern England and southern Scotland suggested that pine trees could have persisted in parts of these regions, despite the lack of physical evidence - paucity of preservational environments [87] (Manning et al 2010). In addition, palynological research in County Clare (western Ireland) has provided tangible evidence of Scots pine survival throughout the later Holocene. An investigation of Aughrim Swamp revealed continuous pine pollen representation to the present-day (with one small decline to 8% TLP) adjacent to mature and stunted pine woodland growing on limestone pavement [88]. A subsequent core from the nearby Rockforest Lough demonstrated sustained high levels of pine pollen (c. 40% TLP) from 1600 BP to the present, supported by historical documentary and macrofossil evidence (lake shore macrofossils dating to c. 3860 BC, Neolithic; a lake core pine wood fragment and a pine needle dated to c. AD 840, early Medieval) [89]. Roche et al concluded that the living trees were therefore likely to be native, sustained in their karstic environment (free-draining substrate combatting waterlogging elsewhere), and by local land ownership (Rockforest Estate), that prevented the intensity of land clearance and tree removal that occurred elsewhere on The Burren.

In the Meres and Mosses Region a recent study of a peat core from Lin Can Moss (Shropshire – 17 km SW of Wem Moss) has revealed a continuous pine pollen curve, although with low abundance (0.3 - 5.4 % TLP), between 6060+/-30 (5198 - 4847 Cal BC) and 270 ± 30 BP (1510 - 1798 Cal AD) [90]. Sassoon et al demonstrated the similarity of Lin Can Moss pine record to previous palynological investigations in the Welsh Marches (north-east Wales and western Shropshire), in contrast to the intermittent representation of pine pollen elsewhere in Wales. As a consequence, Sassoon et al speculated that neighbouring hills and rocky outcrops, and possibly the wider Welsh Marches area could have been a refugial area for Scots pine, with *'isolated trees* [surviving] *in a mixed forest scenario'* [90 p.9], for reasons analogous to Rockforest in western Ireland. These observations are of particular interest when considered alongside the macrofossil record from Shropshire that not only includes the subfossil pine woodland at Wem Moss, but also macrofossils post-dating 4 ka BP, the date traditionally associated with the 'Pine Decline' in the UK and Ireland (see previous discussion and Figure 7).

Conclusion

Analyses of subfossil pine stumps from Wem Moss produced two tree ring-width chronologies spanning 198 and 208 years respectively (dated by radiocarbon to 3015 – 2505 Cal BC), and these are likely to represent a continuum of mire-rooting woodland, that died off around 4 Ka years BP in response to climatic deterioration – a classic 'Pine Decline' scenario encountered in Ireland, the UK and elsewhere north-western Europe.

The extinction of Scots pine in the UK and Ireland at the Pine Decline, outside the areas covered by today's native Caledonian pine woodlands, has however been questioned by a number of ecological and palaeoecological studies from the Meres and Mosses Region and further-a-field. Parallel palynological and macrofossil investigations from western Ireland have demonstrated the likely survival of native pine trees at isolated sites and the continuous presence of pine pollen at sites in the Welsh Marches, has also highlighted this as a possible refugial area for pine. The review of previously-dated pine macrofossils undertaken in this paper lends additional support to these views, with peatland complexes such as Fenn's, Whixall and Bettisfield Mosses demonstrably well-suited to the persistence of bog pine woodland due to their larger geographical areas capable of supporting more varied mosaics of mire vegetation and hydrology. Future genetic comparisons of native Caledonian pine trees (central Scotland) with other living trees from areas such as western Ireland, the Welsh Marches, northern England and southern Scotland are recommended.

This research gives further credence to the survival of native Scots pine in isolated localities in the UK throughout the later Holocene and up to the present-day, also highlighting the difficulties associated in piecing together disparate and sometimes non-existent vegetational records.

Acknowledgements

The author is grateful to Emma Naden who encouraged initial participation in the Meres and Mosses Landscape Partnership Scheme (MMLPS). Shropshire Wildlife Trust (SWT) for their interest in and assistance in sampling the Wem Moss pines. SWT and the Heritage Lottery Fund for funding the ^{14}C dates.

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