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Climatic significance of the marginalization of Scots pine (*Pinus sylvestris* L.) *c.* 2500 BC at White Moss, south Cheshire, UK

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Abstract: Subfossil wood from White Moss, south Cheshire, has become the focus of palaeoenvironmental research employing not only conventional coring, pollen analysis, radiocarbon dating and dendrochronology on pine and oak, but also the exhumation of *in situ* peat areas and dendroecology of the pine ring-width records. Initial dendrochronological research at the site yielded five pine chronologies dating from 3520 to 2462 cal. BC. These and other data indicate three episodes of pine colonization of the mire in the period between 3643 and 1740 cal. BC. Comparison of the pollen and spore records suggest that pine became marginalized at the site *c.* 2500 cal. BC after successive episodes of increased wetness, and this may represent a staged response to climatic deterioration. Two oak chronologies were dated by reference to the Belfast and to English oak master chronologies to 3228–2898 BC and 2190–1891 BC, respectively, showing the possible co-existence of pine and oak on the mire for part of the time. Further dendrochronological work on subfossil pine at the site resulted in a chronology (WM4) that was cross-matched with pine from elsewhere in England, and subsequently dated absolutely to 2881–2559 BC. Detailed dendroecological information, such as fire episodes and periods of environmental stress indicated in the tree-ring records, have been assigned, precisely and accurately, to calendar years in prehistory. The detailed data show the potential for both dendroecological and wider palaeoclimatic and palaeoenvironmental information that may become available from prehistoric bog-pine chronologies, which might then permit precise correlation and comparisons of proxy-climate data between sites.

Key words: Climatic change, *Pinus sylvestris*, pine pollen, pine decline, mid-Holocene, dendrochronology, subfossil wood, Cheshire, UK.

Introduction

In some mires in the British Isles and other parts of northwest Europe, subfossil wood remains are found stratified in peat sections. Tree stumps and trunks can be substantial and their presence in bogs hints at significantly different climates in the past. Their tree-rings can be used to construct chronologies and to infer palaeoenvironmental conditions in the Holocene.

Oak (*Quercus* spp.) has dominated dendrochronology in the British Isles owing to its utility in the building of long tree ring-width chronologies and subsequent applications as a precise dating and calibration tool (Pilcher *et al.*, 1984; Brown and Baillie, 1992; Baillie, 1995). In contrast, the subfossil remains of Scots pine, *Pinus sylvestris* L. (bog pine), have until relatively recently received little attention in terms of detailed palaeoecological research. Bog pine tree-ring records could not be linked to modern dendrochronologies owing to a lack of preserved specimens (either in bogs, other preservational environments or as building materials) during historic and late-prehistoric times. Investigations of bog pine were initially limited to floating tree ring-width chronologies or isolated wood samples loosely dated using radiocarbon assays (Birks, 1975; McNally and Doyle, 1984; Ward *et al.*, 1987; Bridge *et al.*, 1990; Gear and Huntley, 1991). Cross-matching of ring-width records in some of these studies met with only limited success owing to the sensitive ring-width response of the species, particularly from trees that had grown on peat substrates in marginal, end-of-range locations (Bridge *et al.*, 1990).

More recently, the successful cross-matching of subfossil oak and pine records from the same site (Garry Bog) in the north of Ireland (Brown, 1991) has allowed previously floating pine chronologies to be assigned calendar ages. It has also been demonstrated that long-distance cross-matching of pine chronologies is attainable for sites in England (Chambers *et al.*, 1997). This has allowed more accurate dating of pine occurrences on bogs, but has not addressed the reasons for the apparent 'pine decline' witnessed in many palaeoecological records throughout the British Isles *c.* 2500 cal. BC (Blackford *et al.*, 1992; Pilcher *et al.*, 1995a; Edwards *et al.*, 1996; Hall *et al.*, 1996).

This paper presents the results of a detailed palaeoecological reconstruction based on bog-pine micro- and macrofossils from White Moss, Cheshire (Lageard, 1992). The aims of this research were to reconstruct the local and regional vegetational history, to create a dendrochronological record for the mire and to ascertain the timing and duration of pine colonization of the site. In achieving these, it has been possible to review critically the criteria that have been used to confirm the presence of local pine woodland on the basis of pollen data (cf. Bennett, 1984). In addition, because it has been possible to obtain calendar-year ages for some of the pines, this research highlights the potential of dendroecological information contained within the tree-rings of subfossil bog pine and its possible application in detailed, and temporally precise, reconstruction of palaeoecological responses to environmental and climatic change. Dendroecological data from the bog pine chronologies is used in an innovative way to infer periods of environmental stress, which are precisely dated to calendar years.

The study area

White Moss is a former raised mire covering approximately 20 hectares to the west of Alsager in southeast Cheshire, UK (national grid reference: SJ 775500; Figure 1). The site lies between two major concentrations of lowland mire and wetland deposits, those of the Cheshire Plain and those of north Shropshire. In both these areas there is a large number of small lakes, 'meres' and 'mosses' (mires), formed in a landscape created by two major ice advances during the Devensian glacial stage (Sinker, 1962).

White Moss has been exploited extensively for peat and more recently for the underlying sand deposits. One phase of peat extraction at White Moss ended when large quantities of subfossil wood were encountered within the lower peats. It is this subfossil wood, comprising predominantly Scots pine, that was the focus of this research.

Methods

Field sampling

Various approaches have been adopted in order to study and retrieve subfossil wood samples. These range from observing sections of previously cut peat (Gear and Huntley, 1991), to using sub-aqua equipment in Scandinavian lakes (Eronen, 1979). Spatial reconstruction of former forest layers, using these techniques, can at best reveal vertical cross-sections of possible stump layers. Some previous studies have been hampered by the environmentally sensitive nature of peat deposits, but as White Moss has been substantially eroded by commercial mining activities it is no longer viable as an accumulating mire ecosystem and so this was not a constraint. It was therefore possible to dissect undisturbed blocks of peat (6m^2 in plan view) in three 'exhumation areas' to reconstruct the former mire-rooting woodland in three dimensions

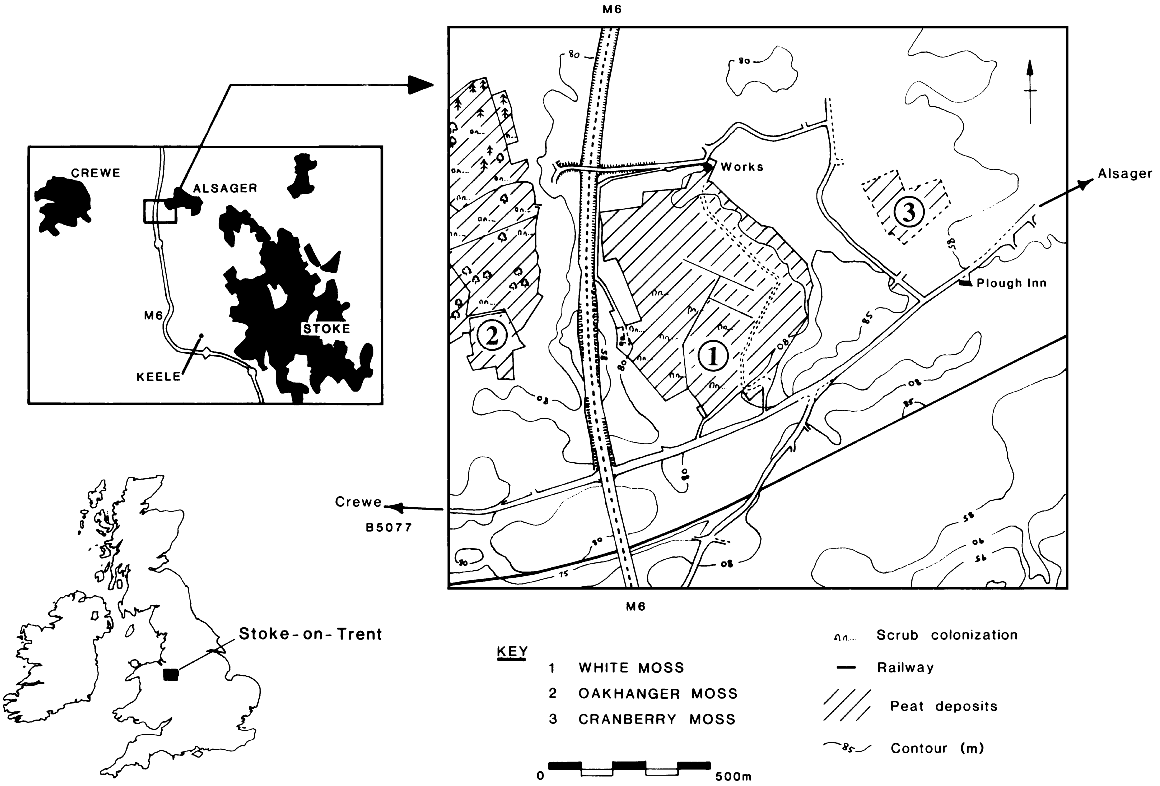

Figure 1 Site location: White Moss, a 20-ha former raised mire, located to the west of Alsager, Cheshire, UK.

Table 1 Nature, provenance and utility for dendrochronology of subfossil wood sampled at White Moss 1988–1993

Sampling area	Subfossil species pine/birch/oak	Pine samples ⩾50 tree-rings	Oak samples >50 tree-rings
Wood piles (WP/K)			
1988–1991	50/0/0	49	
1992–1993	20/0/12	20	12
In situ:			
6III	63/3/0	24	
6II	13/1/0	8	
6I	10/4/1	7	1
Total	156/8/13	108	13

(Lageard, 1992; Lageard *et al.* 1995). Disc samples were removed using chain and bow saws from all stumps and trunks within the three exhumation areas and also from unstratified woodpiles (tree-ring samples with the prefixes WP and K, the discarded biproduct of mechanized peat removal; Table 1). All pine stumps no matter what diameter were sampled in the exhumation areas, in order to reconstruct accurately the macrofossil evidence for former mire woodland layer/s (Lageard *et al.*, 1995). This sampling methodology departs from previous work (cf. Pilcher *et al.*, 1995a) which was biased towards older or larger samples in order to facilitate dendrochronological analyses.

Dendrochronological methods

Sample discs were allowed to air-dry, before being prepared using a belt sander. Progressively finer grit sizes from P60 to P400 (particles of sand/cm^2) allowed the clear differentiation of tree-rings and their boundaries. Tree ring-widths were measured to 0.01 mm using an Atari computer-based system (featuring programs Input10 and Dendro © Ian Tyers). Sample discs were measured along two or three radii and a mean ring-width record was produced for each subfossil pine and oak tree sampled. Sample means with 50 or more rings were compared using computer cross-matching programs based on Baillie and Pilcher (1973) and Munro (1984) (Figure 2). Both programs calculate correlation coefficients at all positions of overlap between the two tree-ring series being compared. Correlations are then expressed as Student's t-values. t-values of greater than 5.0 were usually indicative of a significant cross-match, although this criterion was used cautiously (short sequences of *c*. 50 rings can give spurious correlation values of up to t = 5.50 when compared against longer sequences).

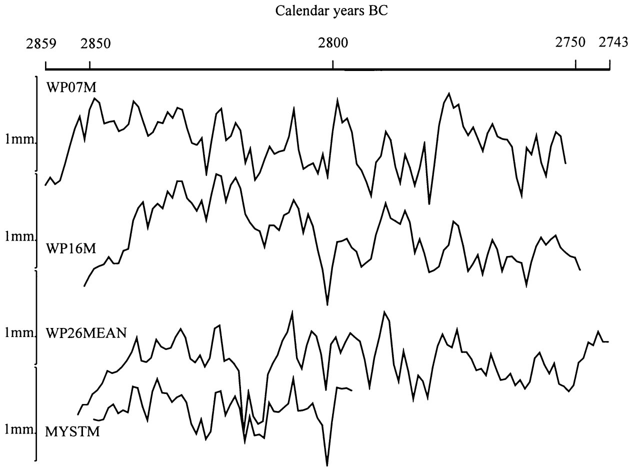

Figure 2 Ring-width graphs (vertical axes employ a semi-logarithmic scale in mm) for Chronology 2 (Lageard, 1992) and constituent trees WP07, WP16, WP26 and MYST.

In comparison with bog pine in Ireland (Pilcher *et al.*, 1995a), White Moss samples were relatively short-lived, with trees rarely exceeding 200 years in age. The most notable exception was BigM (very contorted 338 year ring-width pattern). Barriers to successful cross-matching at White Moss included samples with lobate/eccentric growth or buttress roots. The latter may contain sections of the trunk circumference where there has been a cessation in cambial activity, the 'zone de nécroise' (Munaut, 1966). Where bog pine has experienced extreme environmental conditions, for instance at the limits of its northern range in Scotland, its contorted ring-widths can prove impossible for any dendrochronology (Bridge *et al.*, 1990). Related problems were encountered at White Moss including false, discontinuous, missing rings and very narrow rings. Tree-ring series were also disrupted or lost by poor preservation and by damage through mechanized peat removal. Fire scars also caused problems in initial cross-matching (Pilcher *et al.*, 1995a), but were successfully incorporated in the later stages of chronology building (Chambers *et al.*, 1997). Generally the best cross-matching results were obtained from samples exhibiting regular concentric growth, between 50 and 150 years of age.

Verification of cross-matches was carried out by hand-plotting ring-width series on semi-logarithmic graph paper permitting the identification of missing, discontinuous and false rings or spurious cross-matches.

Peat sampling and palynological methods

A stratigraphic record for the site was made in order to delimit areas still containing subfossil tree stumps *in situ*. This was carried out using a hand-held Jowsey corer along two main transects across the site, northwest to southeast and northeast to southwest (Lageard, 1992). The stratigraphic survey also located areas of deepest Holocene sedimentary accumulation. These sediments were used to reconstruct changes in regional vegetation back to *c*. 11 000 radiocarbon years BP.

Peat monoliths and cores (M1, 6II and 6III ranging from 1.0 to 2.13 m depth) were collected adjacent to the three exhumation areas and were later subsampled for pollen analysis in order to create a pollen record of the former mire-rooting woodland. A longer 6.52 m core (T3.75) was taken from a deeper more central area of the site in order to reconstruct more general regional vegetation history (cf. Jacobson and Bradshaw, 1981).

Laboratory preparation of pollen samples largely followed a standard procedure, after Barber (1976). Pollen identification was made using the pollen identification key from Faegri and Iversen (1975), plates from Erdtman *et al.* (1961 and 1963) and Moore and Webb (1978) and the pollen-type slide collection formerly held in the Palaeoecology Laboratory, Department of Geography, Keele University.

Radiocarbon dating

Important horizons of vegetational change or inferred vegetation dominance were identified in the pollen diagrams. Peat samples from these horizons in pollen cores or monoliths (especially those relating to peaks in the pine pollen curve) were taken for radiocarbon dating. Tree-ring sequences of 20 to 30 years were subsampled from subfossil wood discs in order to establish the age of floating pine chronologies constructed using dendrochronology. In order to test the reliability of the radiocarbon dating, wood samples were taken from both ends of four initial tree ring-width chronologies. Samples were processed in the NERC Radiocarbon Laboratory at East Kilbride. Prior to standard ^{14}C assay, each peat sample was digested in 0.5M hydrochloric acid (at 80°C for 24 hours) and washed in neutral pH. Suspect rootlet material was discarded by hand picking and the shallowest sample then subdivided by wet sieving through a 1-mm steel mesh. Samples were then oven-dried to a constant weight. Wood samples were pretreated by successive digestion (at 80°C) in 2M hydrochloric acid and 2M sodium hydroxide solution to discard soluble extracts. The leeched wood was rendered to cellulose by bleaching in hot sodium hypochlorite solution followed by multiple washing in hot distilled water, also before standard ^{14}C assay (Brian Miller, personal communication).

Results

Palaeowoodland macrofossil record

Table 1 summarizes the nature, provenance and utility for dendrochronology of subfossil wood sampled at White Moss 1988–1993. Of the subfossil tree species sampled, only pine and oak were suitable for dendrochronology, fulfilling the criteria of clearly discernible rings and generally exhibiting a minimum of 50 consecutive rings. Of the 156 subfossil pine trees sampled, 108 were suitable for dendrochronology.

Five pine ring-width chronologies were created (Chronologies 1–5; Lageard, 1992) ranging from 71 to 261 chronology years in length. Wood samples from the start and end of chronologies 1, 2, 3 and 4, and from long-lived individual trees were radiocarbon dated, providing an initial 2σ age estimate for the duration of White Moss mire pine woodland from 3520 to 2462 cal. BC (SRR-3947 and SRR-3945; Table 2).

Later sampling and analyses extended the age estimate for the pine woodland from 3643 to 1740 cal. BC (SRR-6106 and SRR 6103; Table 2). In addition, two subfossil oak chronologies WM1 and WM2 were constructed, which were dated to the calendar years 2190–1891 BC and 3228–2898 BC respectively, with reference to the Irish and North of England master oak chronologies (Table 3).

Further sampling also led to the construction of a new pine chronology (WM4) incorporating samples from Chronologies 2, 3 and 5 (Lageard, 1992) – a total of 26 subfossil pine samples. Table 4 shows a correlation matrix of t-value comparisons between all 26 pine samples included in WM4.

Radiocarbon dates for WM4 when calibrated to 2σ produced an age range of 2895 to 2494 cal. BC (Table 2). The efficacy of the wood sampling and accuracy of the standard radiocarbon dating procedure was corroborated by the subsequent establishing of a calendar age for WM4 of 2881 to 2559 BC (Chambers *et al.*, 1997). The relative dendrochronological positions of WM4 wood samples that were radiocarbon dated can be seen in Figure 3.

Dendroecological evidence for environmental stress

The creation of chronology WM4 has not only permitted the precise dating of some of the pine macrofossils sampled at White Moss, but this tree-ring chronology can also be used to demonstrate that subfossil pine samples contain a significant quantity of previously under-utilized palaeoenvironmental data. Figure 4 is based on the bar diagram for chronology WM4 (shown in Figure

Table 2 Radiocarbon age estimates and their 2σ calibrated age ranges for White Moss subfossil wood samples (pine unless indicated) and for peat samples associated with pollen diagram 6III (~) and from regional pollen diagram T3.75 (+). # indicates samples from chronology WM4; * indicates small diameter pine stumps from regeneration layer C

Laboratory code	Sample	Sample ring-width series dated	Radiocarbon age years BP ± SD	(2σ) Calibrated age range in calendar years
SRR-3939	Big M	1–20	4510 ± 40	3359–3041 cal. BC
SRR-3940	Big M	318–338	4320 ± 50	3082–2785 cal. BC
SRR-3941	# WP 07	1–20	4160 ± 40	2895–2608 cal. BC
SRR-3942	# WP 26	97–117	4125 ± 50	2888–2507 cal. BC
SRR-3943	# WP 06	1–20	4115 ± 40	2880–2510 cal. BC
SRR-3944	# WP 06	90–110	4090 ± 50	2879–2494 cal. BC
SRR-3945	A3.8	1–20	4015 ± 45	2857–2462 cal. BC
SRR-3946	A3.8	73–93	4055 ± 45	2867–2471 cal. BC
SRR-3947	WP C	1–30	4645 ± 35	3520–3347 cal. BC
SRR-3948	WP C	235–265	4500 ± 40	3357–3047 cal. BC
SRR-4500	WP 10	1–20	4505 ± 40	3357–3039 cal. BC
SRR-4501	WP 10	224–254	4335 ± 40	3040–2897 cal. BC
SRR-4502	F6.26	Birch root	4055 ± 40	2865–2483 cal. BC
SRR-4503	F6.26	Birch root	4050 ± 40	2863–2477 cal. BC
SRR-6101	*C6.8	Whole disc	3905 ± 45	2484–2204 cal. BC
SRR-6102	*D3.28	Whole disc	3890 ± 45	2469–2199 cal. BC
SRR-6103	*F2.1	Whole disc	3535 ± 45	1972–1740 cal. BC
SRR-6104	*F5.1	Whole disc	3895 ± 45	2470–2201 cal. BC
SRR-6105	K020	183–203	4210 ± 45	2908–2621 cal. BC
SRR-6106	K021	111–131	4750 ± 45	3643–3373 cal. BC
SRR-6107	WP42	173–193	4305 ± 45	3027–2785 cal. BC

Laboratory code	Peat sample depth (cm)	Radiocarbon age years BP ± SD	(2σ) Calibrated age range in calendar years
SRR-3925 (~)	35.5–36.5	1340 ± 45	cal. AD 629–774
SRR-3926 (~)	61.5–62.5	3650 ± 40	2172–1917 cal. BC
SRR-3927 (~)	117–119	4265 ± 45	3018–2704 cal. BC
SRR-3928 (~)	180–182	5395 ± 45	4351–4047 cal. BC
SRR-3929	193–199	5675 ± 50	4712–4369 cal. BC
SRR-3880 (+)	197–199	5890 ± 45	4931–4686 cal. BC
SRR-3881 (+)	329–331	8625 ± 45	–

Table 3 Summary of tree ring-width chronologies and associated dating from White Moss. * dated by D. Brown with reference to Belfast (BLC7000), North of England (NORENG), East Anglia master oak chronologies and a site master chronology from Croston Moss, Lancashire; # dated via long-distance cross-matching of pine chronologies (Chambers *et al.*, 1997)

Chronology name	number of component trees	length in years	Associated dating ^{14}C (in years BP)/absolute
Chronology 1	3	261	4505 ± 40 BP (SRR-4500) 4335 ± 40 BP (SRR-4501)
Chronology 2	7	131	2873–2743 BC
Chronology 3	4	173	2802–2630 BC
Chronology 4	5	98	4015 ± 45 BP (SRR-3945) 4055 ± 45 BP (SRR-3946)
Chronology 5	2	71	2787–2717 BC
WM1 (oak)	6	300	2190–1891 BC* (t = 5.55 against BLC7000) (t = 7.31 against NORENG) (t = 3.69 against EAST ANGLIA) (t = 7.59 against Croston Moss)
WM2 (oak)	4	331	3228–2898 BC* (t = 4.16 against BLC7000) (t = 5.31 against NORENG) (t = 5.69 against EAST ANGLIA) (t = 3.96 against Croston Moss)
WM3 (pine)	in progress (extension of Chronology 1)	–	–
WM4 (pine)	26 (Includes Chronologies 2, 3 and 5)	323	2881–2559 BC#

3). Once the chronology was completed, component disc samples were re-examined and other important variations in tree-ring morphology were noted. Component trees contain evidence of environmental stresses reflected by sudden changes in the growth patterns. Periods of inferred environmental stress were identified when more than one tree exhibited narrow rings (<0.4 mm), accompanied by mortality in one or more trees.

Using this method of detailed palaeoecological reconstruction, seven specific periods of inferred environmental stress were identified in chronology WM4. These periods are indicated by the arrows and numbers in Figure 4 and are dated to 2800–2794 BC, 2752–2743 BC, 2723–2715 BC, 2702–2701 BC, 2690–2680 BC, 2664–2655 BC and 2639–2626 BC.

The first section of the chronology also contains conclusive evidence for a fire (a significant fire scar in the spring of the year 2800 BC; Chambers *et al.*, 1997) that appeared to act as a rejuvenating influence on the mire-rooting woodland. Other evidence for fire on the outer surfaces of some trees needed to be treated with caution (Leah *et al.*, 1997: 63) as it is likely to stem from modern burning of exposed subfossil wood surfaces.

There is a significant period of inferred environmental stress in WM4 between the years 2752 and 2743 BC (in Figure 4), which included the mortality of four to six trees, narrow ring-width series in three others and the start of a prolonged period of eccentric growth in two more trees (the latter implying trunk leaning due to an unstable substrate). The second section of the chronology from 2743 BC is then characterized by a higher frequency of narrow ring series and increased evidence of stressed trees in the form of compression wood and eccentric growth.

WM4 corresponds with the middle of three consecutive phases of pine woodland at White Moss (see Phase B, Figure 5). Although more recent sampling indicates that these phases are part of a possible continuum of mire-rooting woodland from 3643 to 1740 cal. BC which may be combined at a later date by further dendrochronological sampling and analyses, they do contain significant physical and stratigraphic differences. Phase A included longer-lived trees (up to 338 years in age) probably growing on a shallow peat. In contrast, in Phase B (Chronologies 2, 3, 4 and 5 (Lageard, 1992) and WM4) trees lived from *c.* 50 to 150 years on deeper peats (on average 139 cm above the sand substrate – estimated from *in situ* chronology discs from WM4). This suggests more marginal environmental conditions. By Phase C, trees were growing on an average of 155 cm of peat (estimated in exhumation area 6 × 6III). The pine trees were smaller (an average 12 cm in circumference) and died younger (the majority were <50 years in age at mortality). Phase C trees appear to represent a distinct regeneration layer, since three trees from this phase have been dated to between 2484 and 2199 cal. BC (SRR-6102 and SRR-6101; Table 2). An even younger tree was *in situ* disc F2.1 (166 cm above the underlying sand substrate) with an estimated age range of 1972 to 1740 cal. BC (SRR-6103). The implications of these age estimates are discussed below in relation to the pollen record for the palaeowoodland.

Palaeowoodland pollen record

The macrofossil evidence from White Moss indicates several phases of mire-rooting pine woodland. These were related to the pollen record from three replicated pollen records (6III, 6II and M1), created from monoliths or cores through the peat stratigraphy of the palaeowoodland adjacent to *in situ* exhumation areas. Figure 6 represents a summary pollen diagram for exhumation area 6 × 6III. *Pinus sylvestris* woodland appears to have been increasingly dominant in the south Cheshire region from 8625 ± 50 radiocarbon years BP, reaching its highest pollen representation and also inferred areal extent in the millennium prior to 4900 cal. BC (Figure 5; Lageard, 1992; Atkinson *et al.*, 1999; Innes *et al.*, 1999). However, after 4931–4686 cal. BC pine woodland appears to be increasingly restricted (see SRR-3880, Table 2, and summary of regional pollen diagram T3.75 included as part of Figure 5). The pine pollen record in Figure 6 is likely to be largely representative of pine woodland surviving at White Moss, after being out-competed or excluded from the surrounding regional woodlands (cf. Bennett, 1984).

High *Alnus* pollen and *Alnus* and *Betula* macrofossil evidence from the basal stratigraphy shown in Figure 6 (*c.* 2.0 m depth), indicate an initial alder carr located on a sand terrace at the north and northeast of White Moss. This period (local pollen assemblage zone WMg) is followed by a sustained increase in pine pollen, reaching 54% of the total land pollen count (TLP) *c.* 4351–4047 cal. BC (SRR-3928). A subsequent decline in pine pollen representation is associated with high *Sphagnum* spore counts that can be related tentatively to increasing mire surface wetness. Pine pollen representation again increases towards the end of zone WMh. Zone WMi is then characterized by a significant and sustained increase in *Betula* pollen to a maximum of 61% TLP indicating local birch woodland. Birch pollen declines rapidly at the start of zone WMj and throughout the latter half of the zone there are sustained high values for *Sphagnum* indicating a marked wet

Table 4 A correlation matrix of t-value comparisons between the ring-width records of 26 pine samples from chronology WM4. WM4 includes pine sample records from three previously constructed chronologies; Chronology 2 (*), Chronology 3 (#), Chronology 5 (+) (Lageard, 1992)

	WP	D13M	C322	WP	E314M	WP	WP	MYSTM	WP	K	D2:9	K	K	WP	WP	A410M	WP	K	WP	D215M	WP	WP	WP	WP	WP
	52M			07M		26MEAN	16M		40M	023M		031M	027M	54M	35M		43M	022M	06M		11M	38RM2	04M	41MEAN	47M
WPR39M	3	4.5		5	4.5	4.5	3.4	3.7				3.1	5.1	3.1	3.2										
WP52M *		4.3		6.7	5	5.9	6.1	4.3	3.1		3.1		4.6												
D13M *	4.3			4.4	5.8	4.1	4.8	3.8			4.1	6													
C322M *																									
WP07M *	6.7	4.4			7.7	8.8	7.3	10.8	4.2	4.5	4.5	4.9	6.7												
E314M	5	5.8		7.7		6	5.8	8.9		4	3.4	4.6	4.7												
WP26MEAN	5.9	4.1		8.8	6		8.6	10.6	4.2	3.9	5.5	4.6	6.6												
WP16M *	6.1	4.8		7.3	5.8	8.6		9.4	3.7	3.9	4.8	4.2	5.5												
MYSTM *	4.3	3.8		10.8	8.9	10.6	9.4				5.5	6.7	4												
WP40M	3.1			4.2		4.2	3.7			6.1	4.5	4.4	7	3.6	3.3	3.6	3.9		3.8		3.3	3.2			
K023M				4.5	4	3.9	3.9		6.1		4.1	6.2	7	6.1	4.3	6.3	4.9	6.5	6	7.9	5.7	5.3	7.3	6	
D2:9M	3.1	4.1		4.5	3.4	5.5	4.8	5.5	4.5	4.1		6.5	4.8												
K031M		6		4.9	4.6	4.6	4.2	6.7	4.4	6.2	6.5		5.5				3.9								
K027M	4.6			6.7	4.7	6.6	5.5	4	7	7	4.8	5.5		6.4	4.3	5.7	5.3								
WP54M									3.6	6.1			6.4		4	3.5				3.2					
WP35M #									3.3	4.3			4.3	4		4.4	9.7								
A410M									3.6	6.3			5.7	3.5	4.4		5.7	4.2	3.3	5.1	3.6				
WP43M #									3.9	4.9		3.9	5.3		9.7	5.7									
K022M										6.5						4.2			7.9	6.2	5.9	5.1	7	8.9	5.8
WP06M +									3.8	6						3.3		7.9		9.2	6.6	7	7.4	7.6	5.5
D215MM +										7.9				3.2		5.1		6.2	9.2		7.5	6.4	6.8	6.6	
WP11M +									3.3	5.7						3.6		5.9	6.6	7.5		4.8	5.8		
WP38RM2 +									3.2	5.3								5.1	7	6.4	4.8		4.6	4.2	
WP04M										7.3								7	7.4	6.8	5.8	4.6		6.2	3.8
WP41MEAN										6								8.9	7.6	6.6		4.2	6.2		3.4
WP47M																		5.8	5.5				3.8	3.4	

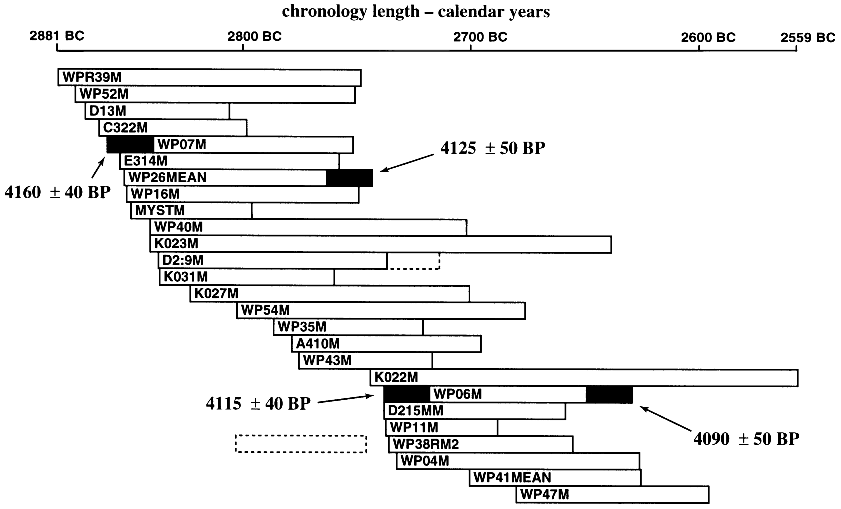

Figure 3 Bar diagram illustrating the relative positions of component ring-width series of pine chronology WM4 from White Moss, Cheshire.

episode on the mire followed by an inferred dry period commencing *c.* 3018–2704 cal. BC (SRR-3927).

There are further significantly high *Sphagnum* counts throughout zones WMk to WMm which appear to be inversely related to the charcoal record. The pine pollen record peaks immediately after 3018–2704 cal. BC (31% TLP) and for a final time in zone WMl at between 2172 and 1917 cal. BC (SRR-3926), reaching 26% TLP. Pine pollen declines to 9% at 50 cm core depth and thereafter to inferred background levels (<3% TLP, except for an isolated peak at 10 cm of 6% TLP).

Although the same pattern of pine pollen representation is apparent from all three replicated pollen diagrams (M1, 6II and 6III) based on peat samples taken through the palaeowoodland layers (Lageard, 1992), there is significant spatial variation in the scale of pine pollen representation. Pine pollen percentages from *c.* 4900 cal. BC to *c.* 1880 cal. BC (from the oldest peats on the sand terrace in the north and northeast of the site, to the estimated age for the last macrofossil evidence for pine at the site) vary between 54–9% (in diagram 6III), 56–8% (6II) and 18–3% (M1).

Discussion

Pine pollen representation

Pine microfossils and macrofossils have played an important part in Holocene vegetational reconstructions in northwest Europe owing to the importance of pine as an indicator species for the northern Boreal forest communities which, in the immediate postglacial period, were widely distributed throughout the British Isles. The precise areal extent of *Pinus sylvestris* was initially estimated by Huntley and Birks (1983) for each millennium from 13 000 radiocarbon years BP on the basis of palynological evidence. These estimates for the local presence of pine woodland surrounding specific depositional environments were based on a criterion of pine pollen representation reaching 25% of the total land pollen count. Huntley and Birks felt it important to use a higher value than for other tree taxa as pine is a prolific pollen producer and the morphology of its pollen grain facilitates wind-borne dispersal.

Other workers have used criterion levels ranging from 20%

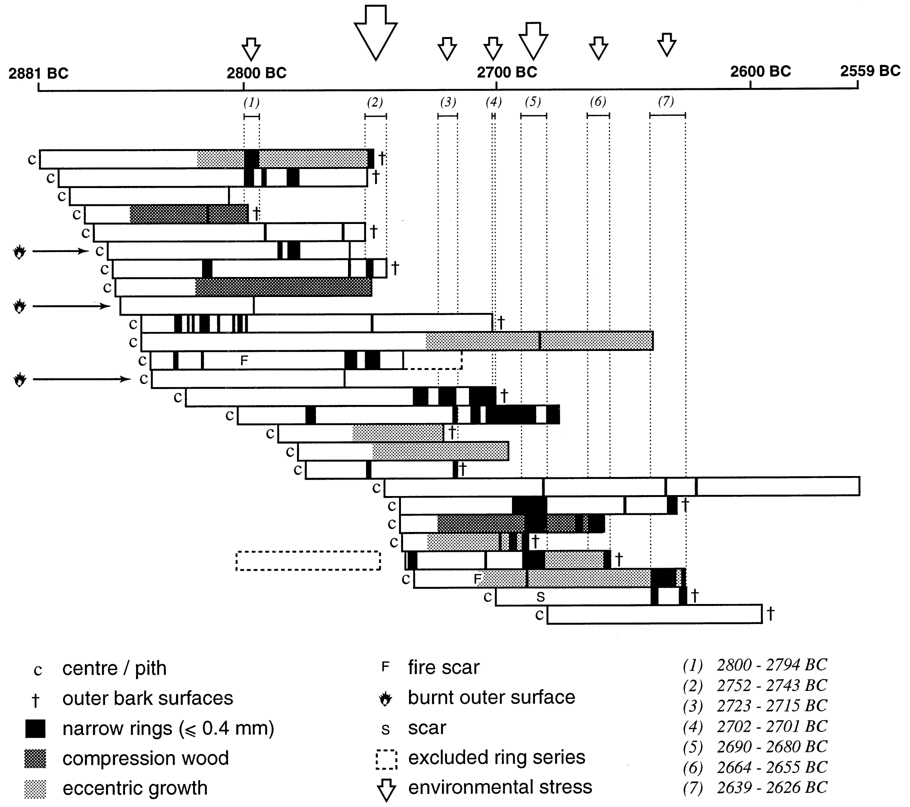

Figure 4 A dendroecological interpretation of chronology WM4.

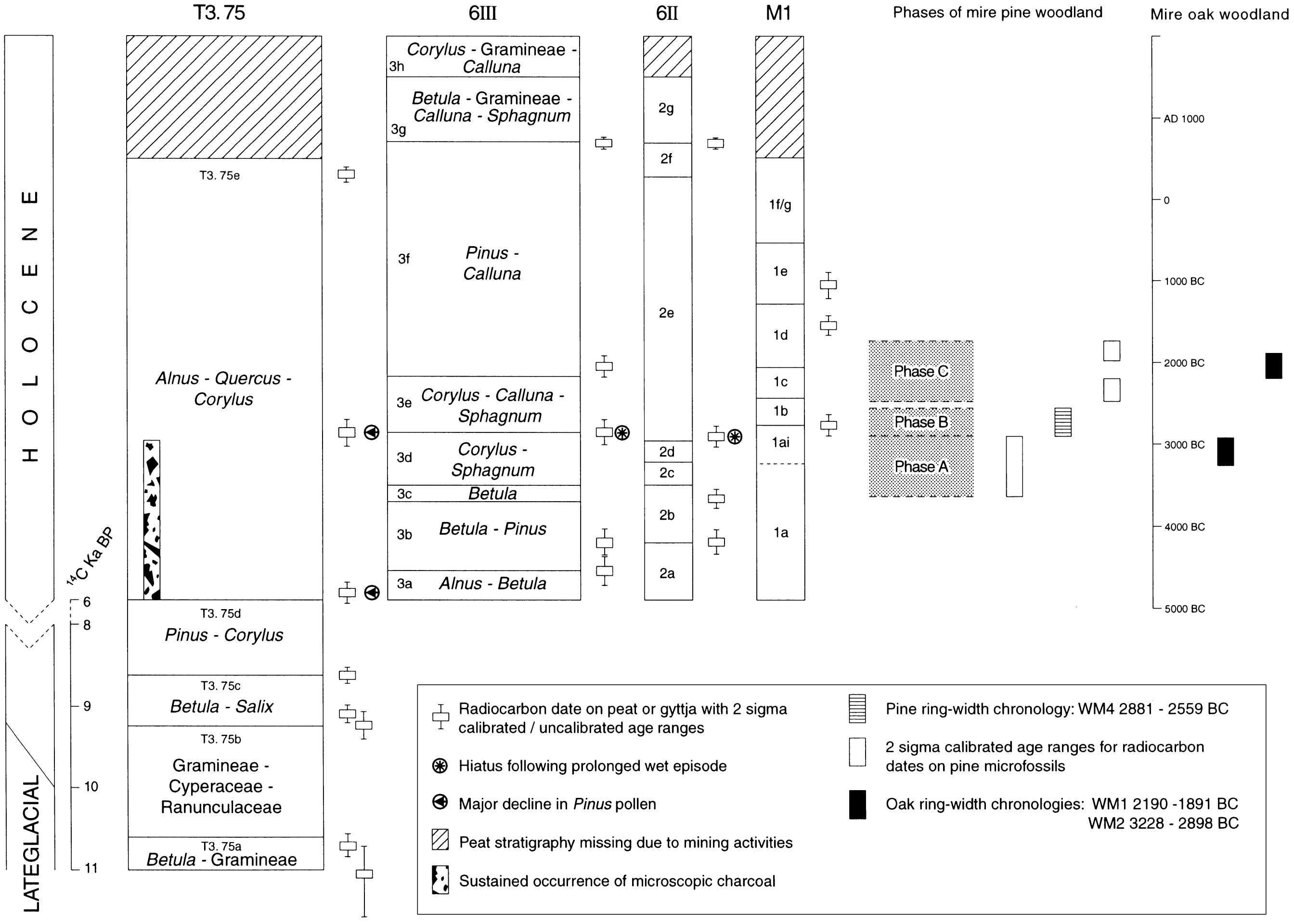

Figure 5 Summary of Lateglacial and Holocene vegetational history at White Moss compiled from pollen, tree-ring and radiocarbon data (adapted from Lageard, 1992).

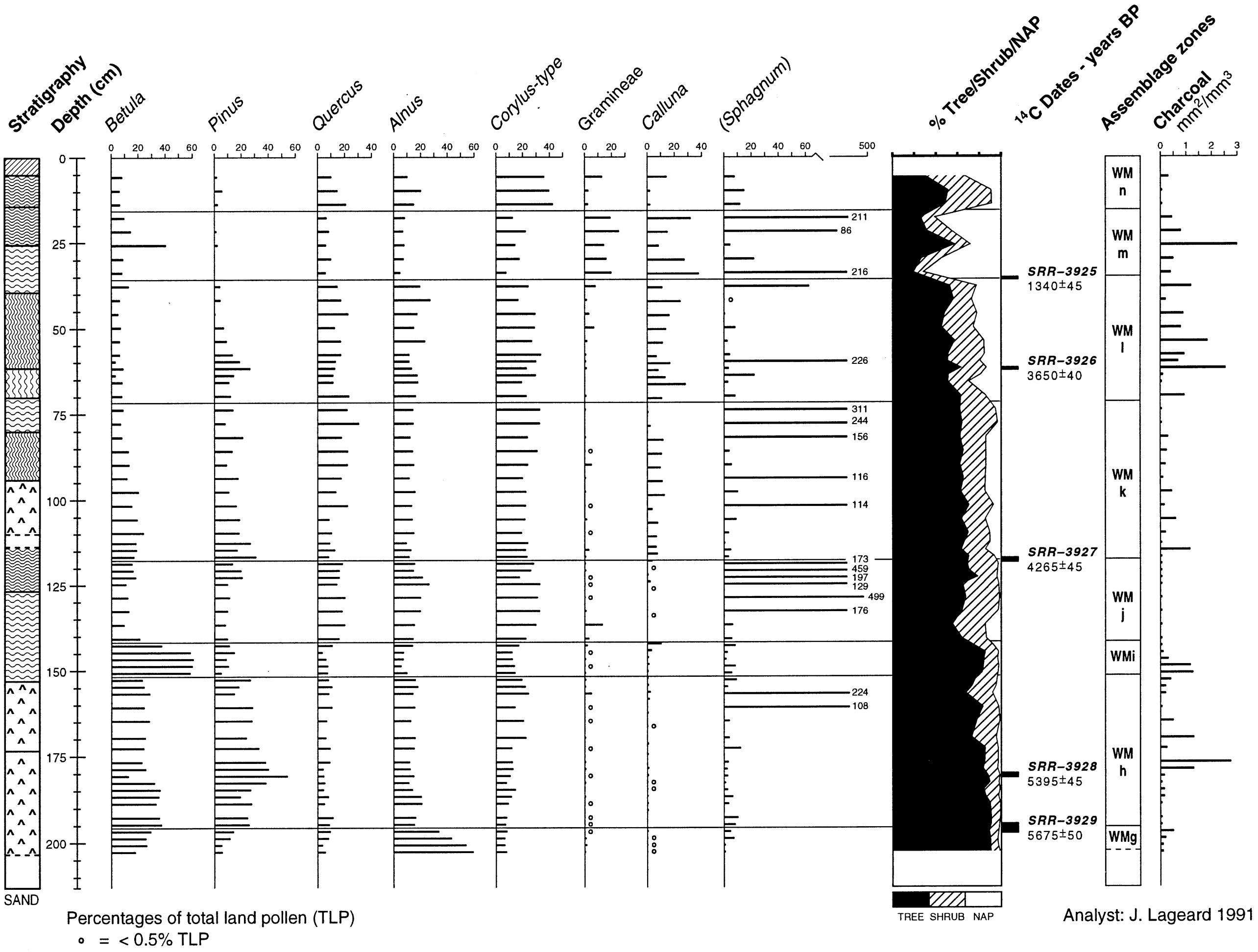

Figure 6 Selected taxa from pollen diagram 6III from peat monoliths and cores sampled at the edge of *in situ* exhumation area 6×6III (Lageard, 1992).

(Bennett, 1984) to 30% TLP (Gear and Huntley, 1991). However, the amount of pollen indicative of local pine trees may be highly variable. Tipping (1989) demonstrated that in an open Lateglacial environment surrounding the Awe valley in western Scotland, long-distance pine pollen representation could rise as high as 40% TLP. However, Bennett (1995) has subsequently revised his initial 20% criterion to 5% total pollen, on the strength of work by Fossitt (1994), where pine stomata were found in lake sediments that contained less than 5% pine pollen. This revision is further supported by dendrochronological analyses in the north of Ireland (Brown, 1991). These have shown that in 3100 BC pine woodland covered the southern end of Garry Bog while pine pollen representation on the dome of the same raised bog was only 5% TLP. Indeed ‘in the last phase of dendrochronologically dated pines in 2700 BC the percentage of pine pollen was 4%’ (Hall *et al.*, 1996: 496).

We also found that, although the temporal patterns of pine pollen representation were largely similar in replicated pollen profiles, there were significant spatial discrepancies (within less than 50 m) in the scale of pine pollen representation. These may be related to the filtering effects of local vegetation or to poor tree growth and pollen productivity as a result of localized hydrological variations. Lageard (1992) concluded, conservatively, that a lower 15% TLP criterion would be a better estimate of local pine woodland at White Moss.

The pine pollen record at White Moss has been related to the last macrofossil evidence for pine woodland in the form of ‘regeneration layer/s’ 2484 to 2199 cal. BC and also possibly 1972–1740 cal. BC. The latter phase appears to postdate a final peak of 26% (61.5–62 cm depth) in the pine pollen curve (Figure 6). At the depth estimated to correspond with *c.* 1880 cal. BC, pine pollen remains around 9% TLP (up to 49.5–50 cm depth) before suddenly declining to <1% TLP at 45.5–46 cm depth. What are assumed to be background levels (<3% TLP) are then maintained until the top of the core except for an isolated peak at 10 cm depth of 6% TLP. Based on these data the pine pollen criteria used to reflect local pine trees at White Moss has been revised to 3–9% TLP.

The above discussion of pine pollen criteria highlights the problems involved in comparisons between pine microfossil and macrofossil remains. A significant barrier to palaeoecological interpretation is the uncertainty that all phases of mire-rooting woodland are preserved. Data from White Moss indicate that subfossil pine trees may represent a continuum of mire-rooting woodland, yet even this detailed investigation of one site reveals inconclusive evidence. For instance the pine pollen peak of 54% TLP, between 4351 and 4047 cal. BC (SRR-3928; Figure 6) is so far unrelated to macrofossil remains of equivalent age. The hydrological and nutrient status of the mire at this time, a fen carr, may however have been unsuitable for colonization by pine seedlings, and earlier high pine pollen representation may therefore be related to rapidly contracting off-mire sources. Bridge *et al.* (1990) suggest that from analyses at Scottish sites it is also unclear whether there is a direct relationship between high pine pollen production and pine macrofossil phases, as the latter may document only the final stages of mire woodland preserved by increasing mire surface wetness.

Problems of matching pine macrofossils to their pollen record have been partially resolved by the absolute dating of ring-width series, but future work needs to combine these with high-precision AMS radiocarbon dating of the pollen fraction from peat samples (cf. Brown *et al.*, 1989) in order to achieve useful comparisons that will allow detailed reconstructions of the pollen dynamics of subfossil pine woodland.

Timing and duration of pine colonization at White Moss

Fossil pollen records indicate that Scots pine woodland colonized large parts of the British Isles in response to postglacial climatic amelioration from *c.* 9500 radiocarbon years BP (Huntley and Birks, 1983). Pine was gradually excluded by more thermophilous deciduous woodland and it was believed that pine became extinct over much of the British Isles during a relatively short period of time, known as the 'pine decline', at approximately 2500 cal. BC (Smith and Pilcher, 1973; Bennett, 1984).

More recent evidence has shown that the pine decline may not be a synchronous event throughout the British Isles. Bridge *et al.* (1990) reviewed 96 radiocarbon dates on pines from Scotland and suggested that there were several major reductions in the extent of pine woodland. They linked the main decline at *c.* 2500 BC (a date also supported by Gear and Huntley, 1991) and other reductions in the numbers of radiocarbon dates to evidence of 'pluvial' episodes (Dubois and Ferguson, 1985) and concluded, with reference to periods of high pine pollen representation, that variation in pine woodland lagged behind the climatic stimuli that triggered them.

Blackford *et al.* (1992), demonstrated a marked decline in pine pollen at two sites in Scotland, associated with a distinctive tephra layer (Hekla-4). A volcanic-related cause of the pine decline in northern Scotland (of 'localized acidic impacts'; Edwards *et al.*, 1996) has been questioned by Hall *et al.* (1994; 1996), from evidence in the north of Ireland, who state that there is no palynological evidence that the Hekla-4 tephra coincided with and contributed to the pine decline. The Hekla-4 isochrone (dated to 2310 ± 20 BC by radiocarbon wiggle-matching Pilcher *et al.*, 1995b, and to 2317 – 2198 BC by Dugmore *et al.*, 1995) is clearly evident in Ireland, but there are no associated fluctuations in pine pollen. There is however oak tree-ring evidence to support the possible impact of Hekla-4 on vegetation, but only between the years 2350–2336 BC (Hall *et al.*, 1994).

Pilcher *et al.* (1995a) review dated pine sequences for Ireland and concluded that 'the survival of macroscopic pine remains in Ireland is episodic and the majority of pine stump dates occur in the millennium centred on 3000 BC'. Brown (1991), cited by Hall *et al.* (1994), established that the last trees sampled stopped growing in the years 2569 BC (at Garry Bog and Sharovogues) and 2642 BC on the Sluggan Bog complex. A radiocarbon dated pine sample from Sharavogues (*c.* 2190 BC) also postdates the date for Hekla-4. There is further evidence for later declines in Irish pine populations at *c.* 2000 BC (McNally and Doyle, 1984), and it is also believed that small pine populations persisted in off-mire locations remote from human populations (Pilcher *et al.*, 1995a). Similar later declines are also noted by Bridge *et al.* (1990) for Scotland and the same is probably true for pine populations in England especially at larger lowland mire sites (Lageard and Chambers, 1993).

In some studies, rapid fluctuations in the representation of pine pollen at *c.* 2500 BC have been demonstrated (Bridge *et al.*, 1990; Gear and Huntley, 1991; Blackford *et al.*, 1992). These however contrast with the evidence detailed in this paper for White Moss, where there is evidence for a series of distinct and declining woodland phases; Phase A, containing long-lived trees back to *c.* 3643 cal. BC; ring-width chronology WM4 dated to 2881–2559 BC (Phase B, supporting a decline around 2559 BC); and Phase C, evidence of regeneration between 2484–2199 cal. BC and 1972–1740 cal. BC. These phases although separated by their stratigraphy and sample characteristics (age/morphology) may in the future be linked by dendrochronology.

Disturbance

A significant disturbance event within Phase B of the mire-rooting woodland is clearly discernible in chronology WM4 between 2752 and 2743 BC, see event (2) in Figure 4, and includes the mortality of at least four trees. The mortality of these trees could be the result of a number of mechanisms including damage by mammals, insects and fungal pathogens; windthrow; fire; and ice (McVean, 1963; Birks, 1975; Blackford *et al.*, 1992). Of these the influence of fire is clearly evident earlier in the chronology in the spring of 2800 BC (Chambers *et al.*, 1997), but there is no evidence to support its role between 2752 and 2743 BC. Other possible agents of tree mortality cannot be discounted, but for event (2) the combination of dendroecological (Figure 4) and pollen/spore data (Figure 6 and evidence discussed below), suggest that an elevated water table was the most likely cause of mortality. Present-day observations of mire-rooting pines have also suggested that similar elevations in water table can cause mortality in cohorts of trees within less than decadal timescales (at sites such as Wybunbury Moss, Cheshire, and Chartley Moss, Staffordshire).

In the second half of chronology WM4 from 2743 to 2559 BC there is little evidence for the regenerative influence of fire, as was apparent after the fire in 2800 BC, and trees are generally shorter-lived and growing in more marginal conditions (based on the dendroecological interpretation of WM4 in Figure 4).

Palynological evidence from White Moss also shows evidence of significant vegetational change throughout the phases of mire-rooting woodland. The hiatus at 3018–2704 cal. BC (SRR-3927) in Figure 6, when related to preceding high *Sphagnum* counts, appears to separate macrofossil evidence for Phases A and B and the associated wet phase would explain the demise of longer-lived pine trees in Phase A and their replacement by shorter phases of pine woodland growing in more marginal conditions (Figure 4). The *Sphagnum* spore record needs to be treated with some degree of caution as direct evidence of mire surface wetness, but its sustained representation throughout considerable periods (Figure 6) probably indicates a succession of wet shifts after 3018–2704 cal. BC. These may correlate with the inferred environmental stress events, such as 2752–2743 BC, explaining tree mortality and the stratigraphic and physical differentiation of Phases B and C.

The microfossil and macrofossil evidence from White Moss support the contention that restrictions in mire-rooting woodland in phase *c.* 2500 BC were a staged response to long-term climatic deterioration. Other studies in the British Isles have concluded that there is a wet shift at the time of the pine decline (Bridge *et al.*, 1990; Gear and Huntley, 1991) and palaeoecological records from Scandinavia indicate a retreat in the northern range of pine forests after 2500 cal. BC thought to be related to climatic deterioration (Eronen and Huttunen, 1987; Kullman, 1989). To this is added palaeoenvironmental evidence for an increasingly wet climate in northwest Europe, such as increased river alluviation in Britain *c.* 3600 to 2700 cal. BC (Macklin and Lewin, 1993).

The environmental conditions that precipitated the main pine decline at *c.* 2500 cal. BC probably had a greater impact on tree populations at end-of-range locations (cf. Blackford *et al.*, 1992), where growth responses would have been more sensitive. Elsewhere in the British Isles there is now a considerable body of evidence supporting a staged retreat in the areal extent of the taxon, particularly on mire refuges where final localized extinctions were eventually inevitable.

Since the initial *in situ* recording of subfossil wood at White Moss (Lageard, 1992), more substantial evidence of oak woodland has emerged in the form of chronologies WM1 and WM2 from unstratified samples located in the eastern part of the site. WM2 coincides with pine Phase A, yet no ring-width cross-matching has so far been possible. It has been noted (Pilcher, 1990) that there are no modern analogues for such mire-rooting oak woodlands and their establishment is often, in Ireland, preceded by an alder carr phase. There are further parallels between White Moss and Irish research in which bog oak and bog pine have co-existed in different parts of the same mire system (Brown, 1991). The reappearance of oak between 2190 and 1891 BC (WM1), at a similar time as the last efforts at regeneration by pine (Phase C), suggests fluctuating surface wetness at White Moss. This runs counter to Irish observations that indicate that the demise of oak woodland can be related to increasing acidity of the peat.

Traditionally bog-pine chronologies have been dated by radiocarbon methods and then compared with pollen records also imprecisely dated by routine radiocarbon dating. Data from White Moss, particularly the dendroecological interpretation of an absolutely dated ring-width chronology WM4, highlights the potential information that can be retrieved from subfossil pine chronologies. Although Baillie (1995: 77) outlines a 'narrowest ring' methodology to illustrate the effects of extreme environmental stress on bog oaks, this type of information only hints at the potential in subfossil wood for dendroecological interpretation. Briffa *et al.* (1990) have shown that a long absolute Scots pine chronology can be used to reconstruct summer temperatures in Fennoscandia over the last *c.* 1400 years, although the sole use of wood density in dendroclimatic reconstructions is cautioned (Swain, 1987; Briffa *et al.*, 1998). As absolute dates are achieved for an increasing number of former floating subfossil pine chronologies detailed dendroecological comparisons will facilitate reconstruction of inter- and intraregional woodland responses to climate change and other environmental stresses with annual resolution.

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