Using fire scars and growth release in subfossil Scots pine to reconstruct prehistoric fires

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Abstract

Fire scars indicating low- to moderate-intensity fires on peat deposits have been sampled from subfossil Scots pine (*Pinus sylvestris* L.) at sites in England, Wales and south-west Ireland. Analysis of ring-width responses to one fire event in 2800 BC illustrates its rejuvenating effect on *Pinus sylvestris* woodland, supporting a growing body of modern and palaeoecological data that illustrates the regenerative role played by fire in persistence of *Pinus sylvestris* woodland. Both the scale and timing of these fires suggest that infrequent low- to moderate-intensity fires are sufficient to stimulate *Pinus sylvestris* growth. This effect is shown by average increases in ring-width following the fire of between 0.62 and 1.16 mm in non-scarred trees and between 0.92 and 2.74 mm in fire-scarred individuals. Growth release in non-scarred trees may prove to be a more reliable method of detecting fire than using the relatively rare fire scars alone. Radii at time of scarring varied between 1.85 and 11.2 cm, much smaller than is predicted to survive from modern studies.

Keywords: dendrochronology; Eire; fire scars; growth release; *Pinus sylvestris*; UK

1. Introduction

There is both palaeoecological and contemporary ecological evidence from north-west Europe supporting the contention that fire is an important influence in perpetuating natural *Pinus sylvestris* L. (Scots pine) woodland on a variety of different substrates (Carlisle and Brown, 1968; Birks, 1975; Zackrisson, 1980; Bradshaw and Zackrisson, 1990; Bradshaw, 1993; Lowe, 1993; Kolstrom and Kellomaki, 1993; Little et al., 1996; Agee, 1998). Palaeoecological records used in reconstructing fire history originate mainly from lakes and mires. Sediment cores from these locations are commonly analysed for pollen and charcoal in order to establish spatial and temporal variation in vegetation communities and also to estimate the incidence of fire (Terasmae and Weeks, 1979; Patterson et al., 1987; Bradshaw and Zackrisson, 1990; MacDonald et al., 1991; Odgaard, 1992; Tipping, 1996; Pitkanen and Huttunen, 1999). Studies of the incidence of fire are hampered, however, by the limitations of radiocarbon dating (cf. Baillie, 1990, 1991; Pilcher, 1993). In addition, the quantification of both micro- and macroscopic charcoal are merely indirect measures of fire, as charcoal can be transported significant distances from original fire sources by various mechanisms (Patterson et al., 1987). Hence estimates of past fire frequency, intensity, and size, and its environmental and climatic significance, are, as noted by Tipping (1996), at best imprecise. In contrast, fire scars recorded within tree-ring series are testimony to the effects of fires in situ, assuming that the scarred trees remain where they grew. Fire scars can be dated from tree-ring chronologies with annual and even seasonal precision (Arno and Sneck, 1977; Tande, 1979; Payette, 1980; Zackrisson, 1980; Sheppard et al., 1988; Baisan and Swetnam, 1990; Ortloff, 1996; Lehtonen and Huttunen, 1997; Agee, 1998; Lehtonen, 1998). Wright and Heinselman (1973) reinforced the view that tree-rings are important for fire history reconstructions, yet for fire records beyond 300–500 years ago they noted that other techniques, such as stratigraphic analyses of pollen and charcoal, needed to be employed. Recent research has shown that calendar dates can also be achieved for prehistoric fire-scarred trees (Chambers et al., 1997), offering exciting possibilities for fire history, environmental and climatic reconstructions in prehistory.

This paper (1) addresses the problems and potentials of relating the ring-width records of fire-scarred trees to prehistoric ring-width chronologies for Scots pine and (2) compares modern pine mortality data as a result of fire (Kolstrom and Kellomaki, 1993) with data from prehistoric fire scars from sites in England, Wales and south-western Ireland.

2. Sites

Fire scars preserved in the tree-rings of subfossil Scots pine have been recorded during wider palaeoenvironmental reconstructions at three lowland mire sites: in north-west England, on the English/Welsh border and south-west Ireland (shown in Fig. 1). The subfossil pine trees sampled during this research grew on peat substrates at the sites and were sampled from combinations of in situ and unstratified localities.

2.1. *White Moss*

White Moss is a former lowland raised mire located to the west of Alsager in south-east Cheshire, England (National Grid Reference SJ 775500). White Moss has been exploited extensively for peat and more recently for the underlying

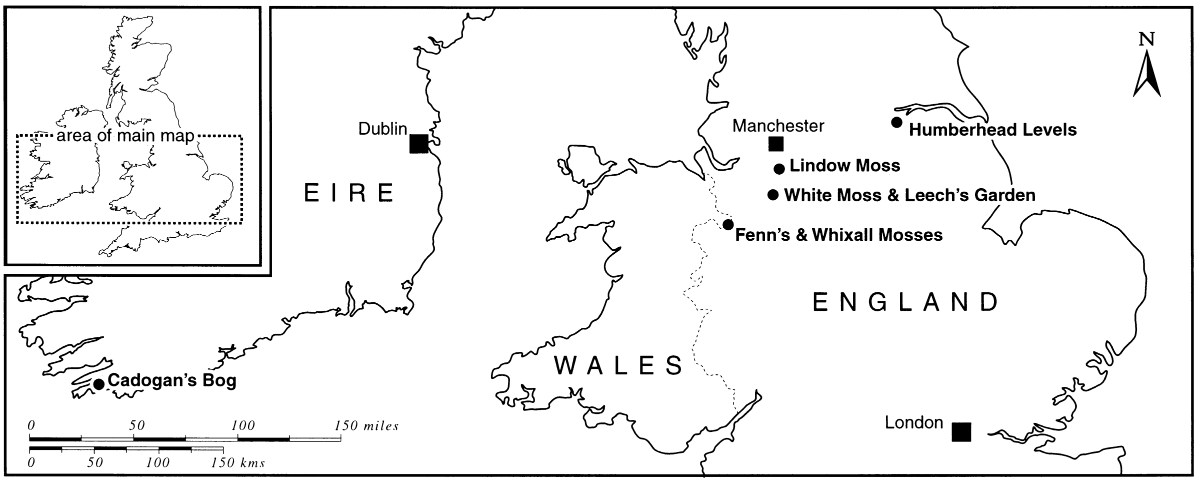


Fig. 1. Map showing the location of sites mentioned in the text: Cadogan's Bog (south-western Eire); Fenn's and Whixall Mosses (English/Welsh border); White Moss, Leech's Garden and Lindow Moss (all in Cheshire, England); Humberhead Levels (eastern England).

sand deposits. One phase of peat extraction ended owing to large quantities of subfossil wood contained within the lower peats. It is this subfossil wood, comprising predominantly Scots pine, that was the focus of research by Lageard (1992). The aims of the research were to reconstruct local and regional vegetation history to assess the timing and duration of pine woodland on the site and to review palynological criteria used to signify the presence of local pine trees (Lageard et al., 1999).

2.2. Leech's Garden

This site is part of a peat-filled hollow adjacent to White Moss (NGR SJ 776 555) and has produced disc samples from six subfossil pine trees, so far undated.

2.3. Lindow Moss

Lindow Moss, a former raised bog located to the west of Wilmslow, Cheshire (NGR SJ 820 805) has a long association with palaeoecological and more recently archaeological research (Birks, 1965; Stead et al., 1986; Turner and Scaife, 1995). The latter has been possible as a result of peat extraction at the site and more recently has revealed a substantial subfossil pine woodland across large areas of the site (Lageard, 1998). Reasons for the establishment and decline of this woodland have been investigated by Roberts (1998).

2.4. Fenn's and Whixall Mosses

This site is an extensive degraded lowland mire system located on the Clwyd/Shropshire border (NGR SJ 490 370). Fire-scarred tree AAP2 was sampled as part of research by Roberts (1998).

2.5. Cadogan's Bog

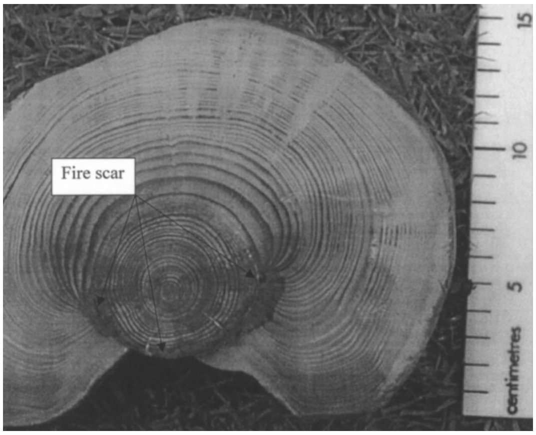
This is one of two sites chosen to illustrate vegetational change during the Holocene on the Mizen Peninsula, south-western Ireland (Mighall and Lageard, 1999). The presence of pine stumps preserved within blanket peat at Cadogan's Bog provided the opportunity to test mechanisms responsible for declining pine woodland during the Holocene, notably at the 'pine decline' (Smith and Pilcher, 1973; Bennett, 1984; Bradshaw and Browne, 1987; Pilcher et al., 1995) ca. 2500 BC.

3. Methods

Detailed methods involved in the vegetational reconstructions for the projects outlined above have been reported elsewhere (Lageard, 1998; Lageard et al., 1999; Mighall and Lageard, 1999). Ring-width series illustrated in Fig. 3 were plotted using Dendro software (Tyers, 1999). Methods involved in defining and ageing fire scars encapsulated within historic and prehistoric pine trees are described here.

3.1. Fire scar analysis and dating

Death of part of the base of a tree by fire can be seen in modern forests (particularly in North America) as tapering scars ('catfaces'; cf. Arno and Sneck, 1977). However, small scars caused by low- to moderate-intensity fires, such as are common in the northern European boreal forests (Agee, 1998), readily overheal and are more difficult to detect (Zackrisson, 1980). Arno and Sneck (1977) provide methodologies for reconstructing fire history using a combination of increment cores and wedge-shaped cross-sections obtained using a chainsaw. There are concerns in sampling living trees (possible direct/indirect mortality or damage to timber grain), but careful use of increment cores can provide a satisfactory method for dating fire scars (Sheppard et al., 1988), although it is possible to miss fire-damaged sections. Examining stumps in clear-cut stands (where scars are readily examined) can allow an accurate fire history record to be built. This luxury can also be possible when sampling subfossil pine preserved within peat deposits, as complete stump cross-sections (discs) can be sampled using a chainsaw. Fire scars in subfossil pine can often be noted in the field by the distinctive regrowth pattern of wood around the scar, but can also be obscured by chainsaw marks or wet peat. Care must be taken not to misinterpret modern charring on outer surfaces of exposed subfossil stumps (Leah et al., 1997, p. 63).


Fire scar
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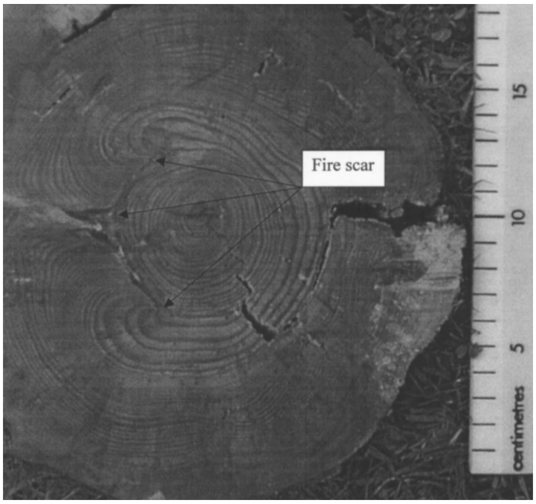
centimetres

(a)

(b)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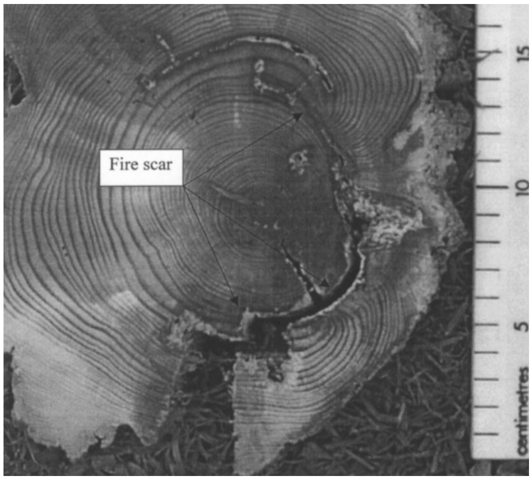
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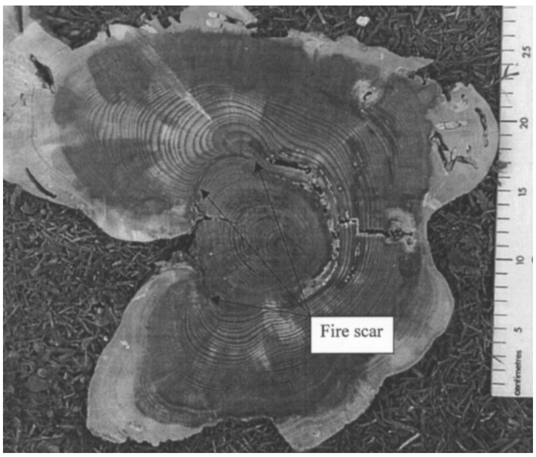
Fire scar
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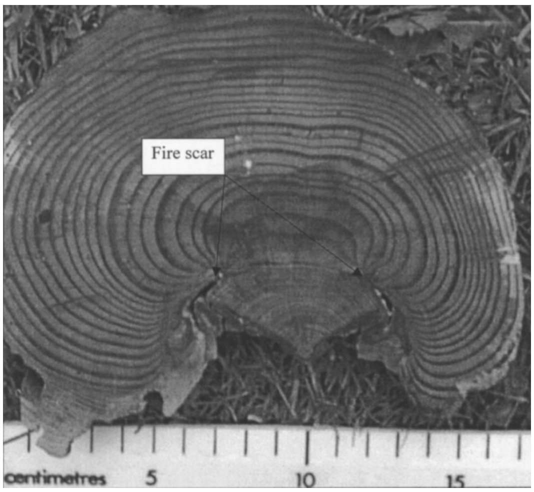
(e)


Fire scar
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(f)

Dendrochronology provides the starting point for dating fire-scarred subfossil pine. In our studies, disc samples were recovered from pine stumps above the root crown, using a combination of chain and bow saws. Samples were allowed to air-dry before being finely sanded using a belt sander. A ring-width record was then made from each sample based on methodology described by Lageard et al. (1999). Computer-assisted cross-matching allowed contemporaneous tree-ring records to be combined to form tree ring-width chronologies. Creation of robust ring-width chronologies (that is, well-replicated chronologies comprising the records of a dozen or more contemporary trees — for example 26 trees in WM4, see results) can lead to the successful later inclusion of additional ring-width series from samples where cross-matching has so far been unsuccessful. These additional chronology components can include the ring-width records of fire-scarred trees (such as D2.9 from White Moss, see Fig. 2a and b) and similar methods have been successful in accurately constructing modern fire histories (Madany et al., 1982). If chronologies can then be dated absolutely (cf. Chambers et al., 1997), the calendar year of the fire or fires can be determined. This procedure is not without problems. The more fire scars there are, the more problematic it is to fit individual trees into a chronology (David Brown, personal communication regarding subfossil pine trees from the early Holocene in Ireland). Anomalous growth patterns resulting from damage by fire and other limiting factors are discussed by Madany et al. (1982) and have caused problems in modern fire history reconstructions in Scots pine-dominated woodland (Zackrisson, 1980). Careful sanding of fire-scarred samples, including the removal of resin obscuring fire-damaged cells (using a sharp blade), provided additional information relating to the season in which the fires occurred. Fig. 2b illustrates scarring burnt into the earlywood of sample D2.9 from White Moss, denoting a spring fire.

3.2. *Growth release*

Analysis of fire-scarred discs showed significant growth release in rings immediately following the year of the fire. Growth release is seen as wider rings in the year(s) following the fire. This was quantified (Tables 1 and 2) as ring-width (mm) in the year of the fire (F) and in the two following years (F + 1, F + 2). The growth release of scarred trees from a variety of sites (Table 1) and of non-scarred trees in chronology WM4 (Table 2) was calculated by (F + 1) − F and (F + 2) − F.

3.3. *Fire severity*

Research on modern sites in Finland, where Scots pine represented 37 and 92% of the woodland basal area, has shown that all pines less than 5 cm in diameter died as a result of a low-intensity prescribed fire (Kolstrom and Kellomaki, 1993). The diameters at time of fire-scarring of the subfossil pines in this study (a range of values in some cases due to sample eccentricity) were therefore measured for comparison with these modern analogues (see Table 1).

3.4. *Radiocarbon date calibration*

Calibration of radiocarbon dates is imperative (cf. Baillie, 1990, 1991; Pilcher, 1991) and was calculated using a radiocarbon calibration program (rev. 2.0, 1987) developed by the University of Washington Quaternary Isotope Laboratory (cf. Pearson et al., 1986). Dating based on radiocarbon dates is expressed in this paper as calibrated years BC (cal. BC).

Fig. 2. (a) A fire scar dated to the year 2800 BC, affecting about half the circumference of subfossil pine disc D2.9 from White Moss, Cheshire. (b) Detail of the fire scar in disc D2.9, ×4.75 magnification, showing that the fire burnt into the earlywood of the tree indicating a spring fire. (c–e) Fire scars encapsulated within pine samples L008, L010 and L046 from Lindow Moss, Cheshire. (f) Damage to an estimated 90% of the cambium of pine sample AAP2 from Fenn's and Whixall Mosses, Clwyd/Shropshire.

Table 1
Details of subfossil pine trees with encapsulated fire scars from sites in Cheshire, Clwyd/Shropshire and County Cork

Site	Sample code	Pith (P)/ outer bark present (B)	No. of sample rings	Age at fire scar	Diameter at fire scar (cm)	% of circumference scarred	Average ring-width (mm)	Ring-widths (mm): fire year (F), F+1, F+2	Growth release (F+1)−F, (F+2)−F	Dating	Fire scar season: earlywood (E), latewood (L)
White Moss	D2.9	P/B	102	38	5.2–5.45	46	0.86	0.62, 1.06, 4.78	0.44, 4.16	2800 BC	E
	D6.37	P/B	111	22	3.0–3.25	50	1.04	1.80, 0.78, 1.30	−1.02, −0.50	–	E
	E6.41	P	74	23	1.85–2.9	23	1.17	1.15, 1.54, 3.20	0.39, 2.05	–	E
	WP04	P/B	107	27	2.05–3.0	50	1.05	1.03, 0.58, 1.08	−0.45, 0.05	–	E
Leech's Garden	LG4	P	131	104	7.7–9.15	–	0.87	1.32, 4.23, 4.10	2.91, 2.78	–	E
Lindow Moss	L008	P/B	145	30	5.9–6.05	40	0.98	1.35, 2.68, 5.42	1.89, 4.07	–	E
	L010	P	128	40	7.55–8.05	43	1.23	0.86, 1.31, 3.64	0.45, 2.78	–	E
	L046	P/B	182	49	9.55–11.2	43	1.16	0.60, 1.68, 3.84	1.08, 3.24	–	E
	K099	P/B	144	67	7.0	–	1.28	0.36, 1.24, 2.81	0.88, 2.45	2563–2139 cal. BC	E
Fenn's and Whixall Mosses	AAP2	P	92	48	2.95–3.7	90	1.47	0.64, 1.04, 8.90	0.40, 8.26	3491–2923 cal. BC	L
Cadogan's Bog	CR017	P	171	38	7.4–6.75	70	1.19	0.87, 4.03, 1.67	3.16, 0.80	5450–5240 cal. BC	L
						Average growth release:			0.92, 2.74		

Table 2
Ring-width reactions of trees in chronology WM4 to a fire event in spring 2800 BC (fire scar D2.9)

Sample	Average ring-width (mm)	Ring-widths (mm): fire year (F), F+1, F+2	Growth release (mm): (F+1)−F, (F+2)−F[a]
WP39	1.10	0.23, 0.16, 0.25	−0.07, 0.02
WP52	0.76	0.20, 0.23, 0.25	0.03, 0.05
D1.3	2.30	Outer rings missing	N/D
WP07	1.07	0.41, 1.17, 2.44	0.76, 2.03
E3.14	1.67	0.46, 1.18, 3.05	0.72, 2.59
WP26	0.74	0.34, 0.99, 1.17	0.65, 0.83
WP16	1.27	0.20, 0.48, 0.87	0.28, 0.67
MYST	1.66	1.41, 2.73, 2.65	1.32, 1.24
WP40	0.91	0.37, 0.81, 1.67	0.44, 1.30
K023	1.43	0.74, 1.90, 2.65	1.16, 1.91
(D2.9)	(0.86)	(0.62, 1.06, 4.78)	(0.44, 4.16)
K031	1.85	0.69, 1.80, 2.37	1.11, 1.68
K027	0.96	0.70, 1.51, 2.34	0.81, 1.64
WP54	0.90	1.83, 2.73, 3.03	0.90, 1.20
			0.62*, 1.16*

[a] Asterisk denotes average growth release excluding fire-scarred sample D2.9.

4. Results

4.1. White Moss and Leech's Garden

Three phases of mire-rooting pine woodland were identified at White Moss between ca. 3643 and 1740 cal. BC, initially on the basis of radiocarbon age estimates. Subsequent long-distance cross-matching using pine ring-width series allowed one period of woodland to be assigned a calendar age 2881–2559 BC (chronology WM4; Chambers et al., 1997; Lageard et al., 1999). WM4 comprised 26 pine samples, combining three floating ring-width chronologies from Lageard (1992). Pine disc D2.9 — an example of a tree incorporated during the latter stages of chronology building — contains an encapsulated fire scar around 46% of its circumference (see Fig. 2a) dated to the year 2800 BC by its inclusion in WM4 (Chambers et al., 1997). Fig. 2b clearly shows the fire scar burnt into the earlywood, and hence the fire occurred in spring. The diameter of tree D2.9 when it was scarred by the fire varied between 5.2 and 5.45 cm. Fig. 3 illustrates the ring-width record for pine tree D2.9 and also for 13 other trees representing the first part of chronology WM4. The fire responsible for scarring D2.9 occurred in spring 2800 BC, and at this time there is no evidence of ring scarring in any other trees in the chronology. There are, however, significant ring-width responses in these trees. 11 of the 13 trees, excluding D2.9, exhibit a significant growth release averaging 0.62–1.16 mm in each of the two years following the fire year. Two further trees, WP39 and WP52, suffered stress in the form of narrow ring-width series (<0.40 mm over seven consecutive years), and D1.3 died, possibly as a direct consequence of the fire. Disc D1.3 had a diameter of 11.8–13.5 cm five years before the fire (outer rings lost due to poor preservation). Details of three other fire-scarred trees (D6.37, E6.41 and WP04) from White Moss and one (LG4) from Leech's Garden, all so far undated, are also included in Table 1 for comparison with D2.9 and fire-scarred samples from the other sites.

4.2. Lindow Moss

Preliminary dendrochronological results indicate three possible woodland phases at the site indicated by radiocarbon age estimates falling between 4343 and 3803 cal. BC, 2563 and 2139 cal. BC, and a later possible 'regeneration' layer so far undated (Lageard, 1998). Some 449 subfossil pine samples have been collected from the site and so far four encapsulated fire scars have been found

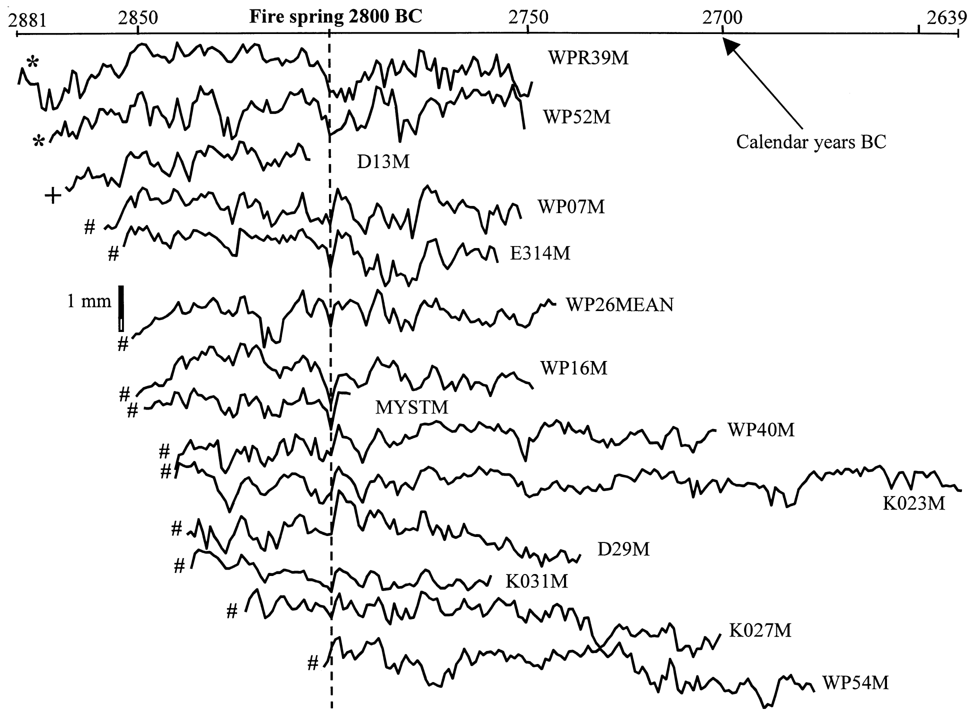

Fig. 3. Ring-width records for pine tree D2.9 and 13 contemporary trees representing the first part of chronology WM4. These synchronised ring-width records illustrate three distinct ecological responses to the fire at White Moss in spring 2800 BC: growth release #, narrow ring series * and also possibly mortality +.

(three of which can be seen in Fig. 2c–e). It is not yet certain whether these scars result from just one fire or several. In the interim, however, these scarred trees do provide data on tree diameter at the time of scarring and subsequent growth release (Table 1), allowing comparisons to be drawn with other sites in this study.

4.3. Fenn's and Whixall Mosses

Pine sample AAP2 is included in this study as it represents the most severely scarred tree (90% of the cambium killed — see Fig. 2f). In addition, AAP2 had a radius of 2.95–3.7 cm at the time of the fire, less than the critical value (5 cm radius) for mortality after fire calculated by Kolstrom and Kellomaki (1993).

4.4. Cadogan's Bog

11 subfossil pine trees were sampled, many of which were poorly preserved, either due to slow incorporation within the blanket peat deposit or to modern exposure to weathering resulting from hand peat cutting. The small sample size and poor preservation have contributed to largely unsuccessful dendrochronological cross-matching for these samples, but one tree, CR017, contained a significant encapsulated fire scar. A radiocarbon date for a 10 year wood sample immediately post-dating the fire scar gave an age estimate of 5450–5240 cal. BC at 2σ (Mighall and Lageard, 1999). CR017 also provides useful comparative fire scar data, see Table 1.

5. Discussion

Modern ecological studies of the boreal forest in America, Europe and Asia have shown that there is a close relationship between fire and the dominance of pines (Agee, 1998). Fire has been shown to play an important part in colonisation and regeneration of *Pinus sylvestris* (Dimbleby, 1953; McVean, 1963; Carlisle and Brown, 1968; Kellomaki, 1987) and similar associations have been inferred for this taxon from palaeoecological records (Bradshaw and Zackrisson, 1990; Bradshaw, 1993; Lageard et al., 1999). The adaptation to fire of various species of pine does however vary considerably depending on the nature of the fire regime, and Agee (1998) uses *Pinus sylvestris* to illustrate a species which generally experiences a moderate-severity fire regime throughout its extensive modern Eurasian range. *Pinus sylvestris* cannot be classed as a 'fire pine', with adaptations such as serotinous cones (Whelan, 1995, p. 97), but in Eurasian boreal forests *Pinus sylvestris* and its subspecies are regarded as the most fire-adapted of trees, with a thick bark, especially under dry conditions (Nikolov and Helmissari, 1992; Agee, 1998). Data presented here give an indication of the effects of fire on mire-rooting *Pinus sylvestris* woodlands in the British Isles in the mid- and early Holocene. It is important to consider these data against the changing nature of fire regimes in north-west Europe during the Holocene, as a result of climatic variability and human intervention, the latter especially in the mid- to late Holocene.

5.1. *Natural vs. human ignition*

Wright and Heinselman (1973) and Johnson (1992) highlight the importance of lightning strikes in igniting fire in the boreal forest, and in northern Europe the role of this agent has been demonstrated during the historic period in northern Sweden (Englemark, 1987). Others argue that "in the latter periods of Man's existence, fire has been used deliberately as a tool for changing the vegetation..." (Dimbleby, 1977, p. 3) and that human ignition is much more likely than lightning-induced fire. Indeed, dendrochronological fire histories using *Pinus sylvestris* have demonstrated the significant effects of slash-and-burn cultivation in shaping forest structure and composition in northern and eastern Finland between ca. AD 1500 and AD 1900, with fire return intervals ranging from 19.2 to 48.8 years (Lehtonen and Huttunen, 1997) and 6.2 years (Lehtonen, 1998; although for one period, AD 1675 to AD 1710, the interval was 2.3 years). At Fenn's and Whixall Mosses, human ignition of peat in the mid-twentieth century has been attributed to local steam railway engines, out-of-control bonfires and fires started deliberately by peatmen (peat cutters), in order to reduce the risk of their plots burning in the subsequent summer (Bill Allmark, personal communication). More recently, on dry mires subject to mechanised peat extraction, low- to moderate-intensity fires (cf. Agee, 1998) have occurred every four to five years since AD 1950 at Fenn's and Whixall Mosses and around every six years since the late 1970s at Lindow Moss (Ken Harwood, personal communication), with ignitions caused by discarded glass and cigarettes. In contrast, fire frequencies for natural dry pine forest during the historic period in Scandinavia have ranged between 40 and 48.8 years (Zackrisson, 1980; Lehtonen and Huttunen, 1997), and in mixed stands the fire return interval has reached 122 ± 81 years (Zackrisson, 1977). In the mid- to late twentieth century, however, fire suppression has virtually eradicated wildfire from some parts of Scandinavia (Pyne, 1995; Agee, 1998). Fire-scarred trees in this study show evidence of specific fire events in prehistory (Table 1). No tree was scarred more than once, indicating a minimum fire return interval of 74 to 182 years. However, low-intensity fires can be overlooked if fire-scarred trees are absent or are not sampled, demonstrating the dangers of fire histories based solely on fire scars. The data in Fig. 3 demonstrate, however, that significant growth release (0.62–1.16 mm) can be seen in a much greater number of trees than would be expected to be scarred, providing a potentially useful indicator for more realistic fire frequencies (possibly in conjunction with fine resolution charcoal analyses). Data from Table 1 suggest that the fire events recorded by the fire-scars from five separate locations were of low to moderate intensity, as these trees continued to grow after scarring of between 23 and 90% of their circumference. Fig. 2f shows scarring around 90% of the estimated circumference of pine disc AAP2. This compares well with observations by Zackrisson (1980), who noted 90% of the cambium killed for one *Pinus sylvestris* tree from the modern European boreal forest. Even fires capable of inflicting such extensive scarring, as demonstrated in this study, do not appear to scar many trees. So even moderate-intensity fires could be particularly hard to detect from fire scars alone. This study validates the use of growth release as an important, but complementary (as growth release may be triggered by other mechanisms), indicator of fire.

Englemark (1987) notes that mires have acted as fire breaks in the natural landscape. Palaeoecological records show that peat surfaces can fluctuate between wet and dry phases, but even when a bog surface is relatively dry there are often mosaics of hydrological conditions which support the evidence outlined above that the effects of mire fires in prehistory were patchy in nature. It is hardly surprising that the effects of a low- to moderate-intensity surface fire at White Moss in spring 2800 BC left a mosaic-type effect on the mire-rooting pine woodland, with one fire-scarred individual and the majority of other trees experiencing growth release (but without any apparent structural damage at the time of the fire). This growth release can probably be related to nutrient release in the form of ash and the burning away of competitors in the field layer and small trees competing for below-ground resources.

Data from Table 1 also provide evidence that can be compared with modern estimates for pine survival after low- to moderate-intensity fire. Kolstrom and Kellomaki (1993) suggest that a diameter of 5 cm is crucial in predicting pine mortality in modern forests. Tree D2.9 from White Moss had a 5.2 to 5.45 cm diameter when 46% of its circumference was scarred in the spring of 2800 BC. D2.9 survived for a further 64 years after this event, although post-fire growth was restricted, witnessed by increasingly narrow rings. Other fire-scarred trees surviving prehistoric fires in this study varied between 1.85 and 11.2 cm in diameter (see Table 1), and D1.3, which may have died probably as a direct consequence of the fire, had a pre-fire diameter of 11.8–13.5 cm. A degree of caution must be exercised in comparing modern ecological and palaeoecological data, as figures for subfossil pine samples invariably underestimate tree size owing to shrinkage of the trees and their disc samples after exposure in and extraction from peat deposits. However, these data for subfossil pine trees suggest that older trees with relatively small diameters may be capable of surviving fire on substrates with variable hydrological conditions. Further, certain trees with comparatively large radii and showing no apparent physical damage to their trunks may experience mortality (pine disc D1.3). This may be the result of damage to the tree canopy or root system.

5.2. *Fire and climate*

The mire-rooting woodland recorded by chronology WM4 grew between 2881 and 2559 BC and is one of three phases of mire woodland probably representing a continuum between 3643 and 1740 cal. BC (Lageard et al., 1999). This vegetation record from White Moss correlates with the latter stages of a distinctly warm climatic phase (Climatic Optimum/Hepsithermal) of the early to mid-Holocene between ca. 6000 and 2500 years BC in which average temperatures have been estimated as 1–2°C higher than present day (Bell and Walker, 1992, p. 70). Comparison of charcoal and pollen records for White Moss suggests that fire was present in regional *Pinus sylvestris*-dominated woodlands in the Cheshire Plain region from ca. 4000 BC and also played an important role on local peat deposits (Lageard et al., 1999). Pollen diagram 6III (Lageard et al., 1999, p. 328) shows an inverse relationship between charcoal and *Sphagnum* spore counts, indicating a series of dry–wet shifts on the local mire surface which resulted in the eventual demise of pine woodland at this refugia site for the taxon. Bradshaw (1993) also correlates events surrounding the pine decline ca. 2500 BC (an episode noted by many authors at sites throughout the British Isles and in Scandinavia; Bennett, 1984; Bradshaw and Browne, 1987; Bridge et al., 1990; Eronen et al., 1999), with increasing climatic wetness and a failure of mire-rooting and other pine woodlands to ignite and therefore to regenerate. Fire-scarred pines from Lindow Moss (2563–2139 cal. BC), Cadogan's Bog (5450–5240 cal. BC) and Fenn's and Whixall Mosses (3491–2923 cal. BC) not only present similar fire scar data to White Moss (Table 1), but reveal a similar picture of fires gradually impeded by increasing climatic/site wetness. There is, however, an intriguing exception to this correlation between fire and mire-rooting pine trees in the British Isles. A series of well-replicated ring-width chronologies has been created for subfossil pines from the Humberhead Levels, eastern England (Boswijk, 1998). Despite extensive sampling of pine and oak woodlands at several sites on the Levels, no fire scars were encountered (Boswijk, personal communication), even in the ring-width chronology PISY, which is the longer contemporary of WM4 (Chambers et al., 1997). Lack of direct evidence of fire in these woodlands may be due to the mosaic effects of low- to moderate-intensity surface fires discussed earlier, or to regional climatic anomalies that may have run counter to modern climatic patterns. This issue can only be resolved in the future by comparisons of wider networks of absolute pine chronologies in both western and eastern parts of the British Isles.

5.3. Modern application

The ring-width responses to the fire event in the spring of 2800 BC at White Moss demonstrate the rejuvenating effects of a low to moderate intensity fire in mire-rooting subfossil *Pinus sylvestris* woodland. Natural regeneration of modern Caledonian forest in Scotland has proved problematic (Sykes, 1987) and, although fire has been traditionally suppressed in the twentieth century, careful use of prescribed fire could be used as a tool for conservation management (cf. Zackrisson, 1980).

Further, detailed study of subfossil pine during the Holocene (cf. Boswijk, 1998; Lageard et al., 1999) may in the future provide detailed regional fire histories in prehistory. Such studies could employ methods such as life-table analysis (age-structure used to estimate time-specific mortality, cf. Larsen, 1996), building on research from North America which has demonstrated significant relationships between ring-width and annual area burned [for Jack pine (*Pinus banksiana*) and White spruce (*Picea glauca*); Larsen and MacDonald, 1995; Larsen, 1996], Such data would provide useful analogues for the responses of the contemporary boreal forest to alleged ‘global warming’, and the predicted increased incidence of fire (Stocks, 1993).

6. Conclusions

This study highlights the problems and the scope of fire history reconstructions using subfossil *Pinus sylvestris* ring-width series. Robust chronologies are essential and care is needed when including fire-scarred trees in these chronologies, since dendrochronological problems are exacerbated when fire scars are more frequent within individual samples and within the subfossil woodlands. Palynological and charcoal data are also vital in the interpretation of fire histories from subfossil fire scars and growth release studies. Future research using subfossil pine chronologies could also trace the pathways of palaeofire events across mire systems using careful sampling of in situ stumps (compass orientations). The creation of more extensive tree-ring chronologies (both temporally and geographically) from the early and mid-Holocene, including fire histories based on growth releases and fire scars, could provide important analogues for fire ecology in modern boreal forests.

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References

Agee, J.K., 1998. Fire and pine ecosystems. In: Richardson, D.M. (Ed.), Ecology and Biogeography of Pinus. Cambridge University Press, Cambridge, pp. 193–208.

Arno, S.F., Sneck, K.M., 1977. A Method for Determining Fire History in Coniferous Forests of the Mountain West. In: USDA Forest Service General Technical Report INT-42. US Department of Agriculture.

Baillie, M.G.L., 1990. Checking back on an assemblage of published radiocarbon dates. Radiocarbon 32, 361–366.

Baillie, M.G.L., 1991. Suck-in and smear: two related chronological problems of the 90s. J. Theor. Archaeol. 2, 12–16.

Baisan, C.H., Swetnam, T.W., 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Can. J. Forest Res. 20, 1559–1569.

Bell, M., Walker, M.J.C., 1992. Late Quaternary Environmental Change: Physical and Human Perspectives. Longman, Harlow.

Bennett, K.D., 1984. Post-glacial history of *Pinus sylvestris* in the British Isles. Quat. Sci. Rev. 3, 133–155.

Birks, H.J.B., 1965. Pollen analytical investigations at Holcroft Moss, Lancashire and Lindow Moss, Cheshire. J. Ecol. 53, 299–314.

Birks, H.H., 1975. Studies in the vegetational history of Scotland IV. Pine stumps in Scottish blanket peats. Proc. R. Soc. London, Ser. B: 270, 181–223.

Boswijk, I.G., 1998. A dendrochronological study of oak and pine from the raised mires of the Humberhead Levels, eastern England. Unpublished Ph.D. Thesis, University of Sheffield.

Bradshaw, R., 1993. Forest response to Holocene climatic change: equilibrium or non-equilibrium. In: Chambers, F.M. (Ed.), Climate Change and Human Impact on the Landscape. Chapman and Hall, London, pp. 57–65.

Bradshaw, R.H.W., Browne, P., 1987. Changing patterns in the Post-glacial distribution of *Pinus sylvestris* in Ireland. J. Biogeogr. 14, 237–248.

Bradshaw, R.H.W., Zackrisson, O., 1990. A two thousand year history of a northern Swedish boreal forest stand. J. Veg. Sci. 1, 519–528.

Bridge, M.C., Haggart, B.A., Lowe, J.J., 1990. The history and palaeoclimatic significance of subfossil remains of *Pinus sylvestris* in blanket peats from Scotland. J. Ecol. 78, 77–99.

Carlisle, A., Brown, A.H.F., 1968. Biological flora of the British Isles: *Pinus sylvestris* L.. J. Ecol. 56, 269–307.

Chambers, F.M., Lageard, J.G.A., Boswijk, G., Thomas, P.A., Edwards, K.J., Hillam, J., 1997. Dating prehistoric bog-fires in northern England to calendar years by long-distance cross-matching of pine chronologies. J. Quat. Sci. 12, 253–256.

Dimbleby, G.W., 1953. Natural regeneration of pine and birch on the heather moors of north-east Yorkshire. Forestry 26, 41–52.

Dimbleby, G.W., 1977. Ecology and Archaeology. In: Studies in Biology 77. Arnold, London.

Englemark, O., 1987. Fire history correlations to forest type and topography in northern Sweden. Ann. Bot. Fennici 24, 317–324.

Eronen, M., Hyvarinen, H., Zetterberg, P., 1999. Holocene humidity changes in northern Finnish Lapland inferred from lake sediments and submerged Scots pines dated by tree-rings. Holocene 9, 569–580.

Johnson, E.A., 1992. Fire and Vegetation Dynamics: Studies from the North American Boreal Forest. Cambridge University Press, Cambridge.

Kellomaki, S., 1987. Metsaekologia Silva. Carelica 7, University of Joensuu (in Finnish).

Kolstrom, T., Kellomaki, S., 1993. Tree survival in wildfires. Silva Fennica 27, 277–281.

Lageard, J.G.A., 1992. Vegetational history and palaeoforest reconstruction at White Moss, south Cheshire, UK. Unpublished Ph.D. Thesis, Keele University, UK.

Lageard, J.G.A., 1998. Dendrochronological analysis and dating of subfossil *Pinus sylvestris* L. at Lindow Moss, Cheshire. Bull. Br. Ecol. Soc. 29, 31–32.

Lageard, J.G.A., Chambers, F.M., Thomas, P.A., 1999. Climatic significance of the marginalisation of Scots pine (*Pinus sylvestris* L.) circa 2500 BC at White Moss, Cheshire, UK. Holocene 9, 321–331.

Larsen, C.P.S., 1996. Fire and climate dynamics in the boreal forest of northern Alberta, Canada, from AD 1850 to 1989. Holocene 6, 449–456.

Larsen, C.P.S., MacDonald, G.M., 1995. Relationships between tree-ring widths, climate, and annual area burned in the boreal forest of Alberta. Can. J. Forest Res. 25, 1746–1755.

Leah, M.D., Wells, C.E., Appleby, C., Huckerby, E., 1997. The Wetlands of Cheshire. In: North West Wetland Survey 4. Lancaster University Archaeology Unit, Cheshire County Council.

Lehtonen, H., 1998. Fire history recorded on pine trunks and stumps: influence of landuse and forest fires on forest structure in north Karelia. Scand. J. Forest Res. 13, 462–468.

Lehtonen, H., Huttunen, P., 1997. History of forest fires in eastern Finland from the fifteenth century AD — the possible effects of slash-and-burn cultivation. Holocene 7, 223–228.

Little, D.J., Mitchell, F.J.G., von Engelbrechten, S., Farrell, E.P., 1996. Assessment of the impact of disturbance and prehistoric *Pinus sylvestris* on the vegetation dynamics and soil development in Uragh Wood, SW Ireland. Holocene 6, 90–99.

Lowe, J.J., 1993. Isolating the climatic factors in early- and mid-Holocene palaeobotanical records from Scotland. In: Chambers, F.M. (Ed.), Climate Change and Human Impact on the Landscape. Chapman and Hall, London, pp. 67–82.

MacDonald, G.M., Larsen, C.P.S., Szeicz, J.M., Moser, K.A., 1991. The reconstruction of Boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological and geochemical indices. Quat. Sci. Rev. 10, 53–71.

Madany, M.H., Swetnam, T.W., West, N.E., 1982. Comparison of two approaches for determining fire dates from tree scars. Forest Sci. 28, 856–861.

McVean, D.N., 1963. Growth and mineral nutrition of Scots pine seedlings on some common peat types. J. Ecol. 51, 657–670.

Mighall, T.M., Lageard, J.G.A., 1999. The environmental context: vegetational history of the Mizen Peninsula. In: O'Brien, W. (Ed.), Sacred Ground: Megalithic Tombs in Coastal South-west Ireland. Bronze Age Studies No. 4. Department of Archaeology, National University of Ireland, Galway, pp. 41–59.

Nikolov, N., Helmissari, H., 1992. Silvics of the circumpolar boreal forest tree species. In: Shuggart, H., Leemans, R., Bonan, G. (Eds.), A Systems Analysis of the Global Boreal Forest. Cambridge University Press, Cambridge, pp. 13–84.

Odgaard, B.V., 1992. The fire history of Danish heathland areas as reflected by pollen and charred particles from lake sediments. Holocene 2, 218–226.

Ortloff, W., 1996. Wood-anatomical evidence of fire seasonality, Tree Rings, Environment and Humanity. In: Dean, J.S., Meko, D.M., Swetnam, T.W. (Eds.), Radiocarbon. University of Arizona, Tuscon, USA.

Patterson, W.A., Edwards, K.J., MacGuire, D.J., 1987. Microscopic charcoal as a fossil indicator of fire. Quat. Sci. Rev. 6, 3–23.

Payette, S., 1980. Fire history at the treeline in Northern Quebec: a paleoclimatic tool. In: Proc. Fire History Workshop. General Technical Report RM-81. US Department of Agriculture, pp. 126–131.

Pearson, G.W., Pilcher, J.R., Baillie, M.G.L., Corbett, D.M., Qua, F., 1986. High-precision 14-C measurement of Irish oaks to show the natural 14-C variations from AD 1840 to 5210 BC. Radiocarbon 28, 911–934.

Pilcher, J.R., 1991. Radiocarbon dating. In: Smart, P.L., Frances, P.D. (Eds.), Quaternary Dating Methods: A Users' Guide. Technical Guide No. 4. Quaternary Research Association, Cambridge, pp. 16–36.

Pilcher, J.R., 1993. Radiocarbon dating and the palynologist: a realistic approach to precision and accuracy. In: Chambers, F.M. (Ed.), Climate Change and Human Impact on the Landscape. Wiley, New York, pp. 23–32.

Pilcher, J.R., Baillie, M.G.L., Brown, D.M., McCormac, F.G., MacSweeney, P.B., McLawrence, A.S., 1995. Dendrochronology of subfossil pine in the north of Ireland. J. Ecol. 83, 665–672.

Pitkanen, A., Huttunen, P., 1999. A 1300 year forest-fire history at a site in eastern Finland based on charcoal and pollen records in laminated lake sediment. Holocene 9, 311–320.

Pyne, S.J., 1995. World Fire. Henry Holt and Co, New York.

Roberts, L.J., 1998. Environmental aspects of bog pine establishment and decline in central Britain during the Holocene. Unpublished Ph.D. Thesis, University of Bristol, UK.

Sheppard, P.R., Means, J.E., Lassoie, J.P., 1988. Cross dating cores as a non-destructive method for dating living, scarred trees. Forest Sci. 34, 781–789.

Smith, A.G., Pilcher, J.R., 1973. Radiocarbon dates and vegetational history of the British Isles. New Phytol. 72, 903–914.

Stead, I.M., Bourke, J.B., Brothwell, D. (Eds.), Lindow Man: The Body in the Bog 1986. British Museum Publications.

Stocks, B.J., 1993. Global warming and forest fires in Canada. Forest. Chron. 69, 290–293.

Sykes, J.M., 1987. Further observations on the recovery of vegetation in the Caledonian pinewood of Coille Creagloch after fire. Trans. Bot. Soc. Edinburgh 45, 161–162.

Tande, G.F., 1979. Fire history and vegetation pattern of coniferous forests in Jasper National Park, Alberta. Can. J. Bot. 57, 1912–1931.

Terasmae, J., Weeks, N.C., 1979. Natural fires as an index of paleoclimate. Can. Field Natur. 93, 116–125.

Tipping, R., 1996. Microscopic charcoal records, inferred human activity and climate change in the Mesolithic of northernmost Scotland. In: Pollard, T., Morrison, A. (Eds.), The Early Prehistory of Scotland. Edinburgh University Press, Edinburgh, pp. 39–61.

Turner, R.C., Scaife, R. (Eds.), Bog Bodies: New Discoveries and New Perspectives 1995. British Museum Press.

Tyers, I., 1999. Dendro for Windows Program Guide, second ed., ARCUS Report 500.

Whelan, R.J., 1995. The Ecology of Fire. Cambridge University Press, Cambridge.

Wright, H.E., Heinselman, M.L., 1973. The ecological role of fire. Quat. Res. 3, 319–328.

Zackrisson, O., 1977. Influences of forest fires on the northern Swedish boreal forest. Oikos 29, 22–32.

Zackrisson, O., 1980. Forest fire history: ecological significance and dating problems in the north Swedish boreal forest. In: Stokes, M., Dietrich, J. (Eds.), Proc. Fire History Workshop. USDA Forest Service General Technical Report RM-181. US Department of Agriculture, pp. 120–125.