Research paper

The Holocene
1–12

DOI: 10.1177/0959683610365935
http://hol.sagepub.com
SAGE

Dendrochronological evidence for a lower water-table on peatland around 3200–3000 BC from subfossil pine in northern Scotland

A.K. Moir,[1,2] S.A.G. Leroy,[1] D. Brown[3] and P.E.F. Collins[1]

Abstract

Tree-ring analysis of subfossil *Pinus sylvestris* L., from nine new peatland sites located beyond the species' current northern limit in Scotland, established a regional chronology called WRATH-9. The chronology has been provisionally dated against Irish pine chronologies and provides the first annual resolution picture of Scots pine expansion from *c.* 3200 BC and subsequent demise from *c.* 3000 BC. Pine germination and growth is suggested to be associated with a widespread fall in bog water-tables that indicates a regional climatic control. Bog pines progressively declined in number, rather than died out in a single event, reflecting their growth in a marginal habitat, close to a critical ecological threshold. The use of tree-ring sequences from *in situ* bog pine macrofossils provides a higher resolution insight into past conditions than possible with existing radiocarbon and pollen-based chronologies.

Keywords

climate change, dendrochronology, pine decline, *Pinus sylvestris*, Scotland, subfossil wood

Introduction

The climate of the Holocene Epoch has varied significantly (Bell and Walker, 2005; Mayewski *et al.*, 2004), although the exact nature and consequence of change is still far from being fully understood. Understanding the pattern and impact of climate change in the past allows for a better appreciation of possible future conditions under a global warming scenario. This paper examines the record of a period of climatic change in the middle Holocene using tree-ring sequences from sensitive bog sites in northern Scotland.

Fluctuations in the range and altitude of Scots pine (*Pinus sylvestris* L.) over northern Scotland during the Holocene have been widely interpreted as the species responding to climatic change, because of the apparent synchronicity of changes over large distances (Anderson *et al.*, 1998; Bennett, 1984; Birks, 1975; Bridge *et al.*, 1990; Dubois and Ferguson, 1985; Gear and Huntley, 1991; Huntley *et al.*, 1997). However, attempts to define the timing of these changes with greater precision have relied predominantly on palynological evidence and radiocarbon dating, whose reliability may be questioned because of a number of intrinsic problems:

- fossil stomata reveal the presence of pine up to 1600 years prior to the dates indicated from the 20% pine pollen level commonly used to interpret its local presence (Froyd, 2005);
- short local occurrences of Scots pine can be missed in the pollen record because of lack of subcentennial resolution (Charman, 1994);
- an apparent discrepancy of up to about 700 years between the ^{14}C ages from wood and those from peat has been attributed to the contamination of peat by younger material (Birks, 1975; Charman and Garnett, 2005; Gear and Huntley, 1991)
- radiocarbon dating is imprecise (Baillie, 1990; Pilcher, 1991). In the absence of high-resolution dating, interpolated dates can be subject to unknown errors with possible occurrences of hiati or changes in accumulations rates.

Hence, the precise characteristics and timing of these episodes of climatic change remain ill defined and have rarely been directly tested by obtaining independent measures (Tipping, 2007; Tipping *et al.*, 2006).

The peatlands of northern Scotland today are one of the largest most intact areas of blanket bog in the world (Stroud *et al.*, 1987) and are predominantly treeless. Nevertheless, extensive horizons of subfossil pine found in these peatlands (Figure 1) demonstrate that this environment has at times become suitable for the mass colonisation by pine. Ombrotrophic bogs are particularly sensitive indicators of climate as they receive their water and nutrient supply from atmospheric precipitation. Very little lateral flow of water across their surface occurs and so in the absence of changes in drainage, the water-table variation is determined largely by the balance between rainfall and evapotranspiration (Lindsay, 1995). Excess water in peat leads to anaerobic conditions where low oxygen supplies and lack of carbon dioxide removal can become a limiting

---

[1]Brunel University, UK
[2]Tree-Ring Services, UK
[3]Queens University, Belfast, UK

Corresponding author:
A.K. Moir, Plough House, 49 High Street, Hungerford RG17 0NE, UK
Email: amoir@tree-ring.co.uk

factor for tree growth (Lähde, 1969). Nitrogen and Potassium are often very deficient on mires (Birks, 1975) and this hinders the establishment of pine (Mighall *et al.*, 2004). The elevation of water-tables depresses growth partly because of nutrients being made less available in poorly aerated soil (Mannerkoski, 1991). Research by Succow and Joosten (2001) showed that changes in site hydrology mainly affect and control nutrient supply in the rootable layer and thus control woodland development in peatlands. Thus, bogs in oceanic areas are treeless; while trees may grow on continental bogs, probably because of their relatively low summer water-tables (Schouten *et al.*, 1992). Mackenzie and Worrel (1995) conclude that Scotland's climate is marginal for the growth of natural tree stands on bogs, except in the Eastern Highlands, where the more continental climate is favourable.

Control of annual growth of trees by environmental factors, particularly climate, is often strong and most clearly discernable in areas where trees grow in marginal environments (Schweingruber *et al.*, 1979). In Scotland today only a remnant population of pinewoods survive. These lie between 56°22′—57°57′ north and longitude 2°53′–5°38′ west (Carlisle and Brown, 1968), at the western limit of this species in northern Europe (Ennos, 1991). In the British Isles, a number of dendrochronological studies have shown the potential of subfossil pine as an important source of calendar-dated palaeoecological and palaeoclimatological information (Brown, 1991; Boswijk and Whitehouse, 2002; Lageard *et al.*, 1999; Pilcher *et al.*, 1995). However, this potential remains largely unexplored (Chambers *et al.*, 1997). Since early attempts at Rannoch Moor in Scotland failed to crossmatch 200 samples (Bridge *et al.*, 1990; Hughes, 1987) and similar difficulties occurred at Lochstrathy (Gear, 1989), there have been few dendrochronological studies on subfossil pine in Scotland. Problems at these sites were probably caused by the lack of a single horizon of pine and generally by the presence of young trees, which led to short tree-ring series. Subsequent investigations (Daniell, 1997; Moir, 1996; Tipping *et al.*, 2007) show the existence of sites without these problems elsewhere in Scotland.

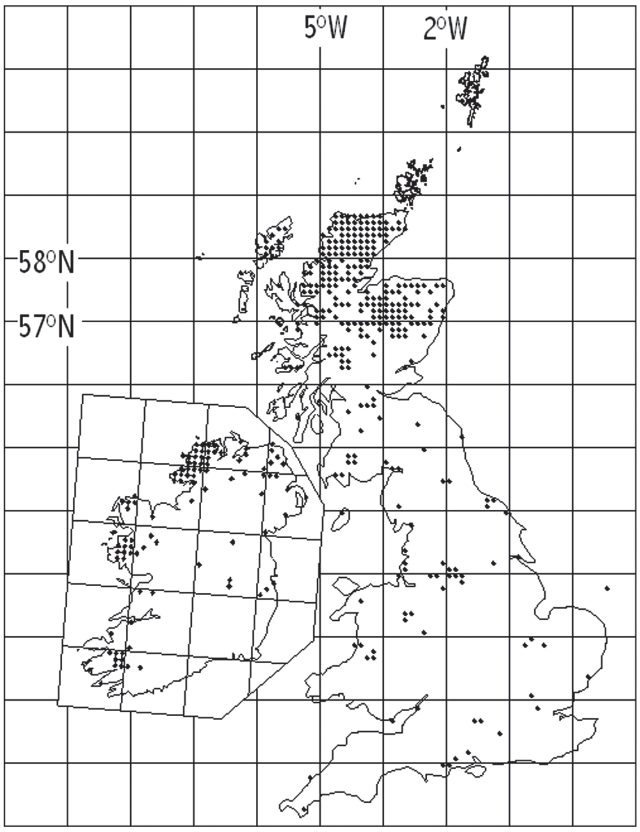

Figure 1. Occurrence of Holocene subfossil pine macroremains in the British Isles (Bennett, 2005). The 100 km squares of British National and Irish Grids are shown, but some closely corresponding Latitudes and Longitudes labelled

The aim of this research is to investigate the dendrochronological potential and climatic significance of subfossil pine widely occurring across the peatlands of northern Scotland. The focus is on a group of broadly coeval populations located beyond the current northern limit of pine in Scotland (58° north, Figure 1), dated by radiocarbon to 3400 and 2200 cal. BC (Gear and Huntley, 1991), with special emphasis on the modes of their expansion and final demise.

Methods

Sampling strategy

Reservoir lochs and peat workings provided the most extensive exposures (Figure 2, Table 1). Sites where ten or more *in situ* pine stumps, containing at least 150 rings and surviving with bark were sought for sampling because of their reasonable dendrochronological potential.

The term 'subfossil' refers to the absence of lithification. Very few trunks were located and therefore most samples derived from stumps. Stumps were excavated down to the trunk/root collar interface, to expose the best-preserved areas, to allow the identification of the year of germination and to maximise the numbers of rings for analysis. Heavily eroded stumps were avoided. Stump height was measured down to the trunk/root collar interface, which was taken to be where the roots begin to flatten out from the trunk. A distinctive shape of root called 'I' girder root has long been recorded in pine growing in peat in Scotland (Anonymous, 1964). These roots are associated with the horizontal development of a shallow root system together with the absence of a vertical tap root and are common to all the sites investigated. Where erosion exposed parts of these extensive root systems, the maximum root depth was recorded.

Sample preparation and measurement

Full horizontal sections were cut by chainsaw and allowed to air dry. Samples were then progressively sanded down to a 600 abrasive grit finish to reveal the tree rings. Any subsequent sanding was done by hand. Tree-ring sequences were measured under a ×20 stereomicroscope to an accuracy of 0.01 mm using a microcomputer-based travelling stage. Missing rings were found to occur during consecutive years of extremely narrow rings (under 0.20 mm/yr), particularly in the first or final 50 years growth. Where a suspected missing ring could not be resolved by careful visual examination of the sample or comparisons with mean series, all the rings prior to, or beyond it, were only counted and not measured. In most cases three different radii were measured from each section and averaged into a single tree-ring series. Mean sensitivity (Table 1) is a measure of the mean relative change between adjacent ring widths. Values over 0.20 are high and indicate the tree-ring series are highly responsive to environmental factors.

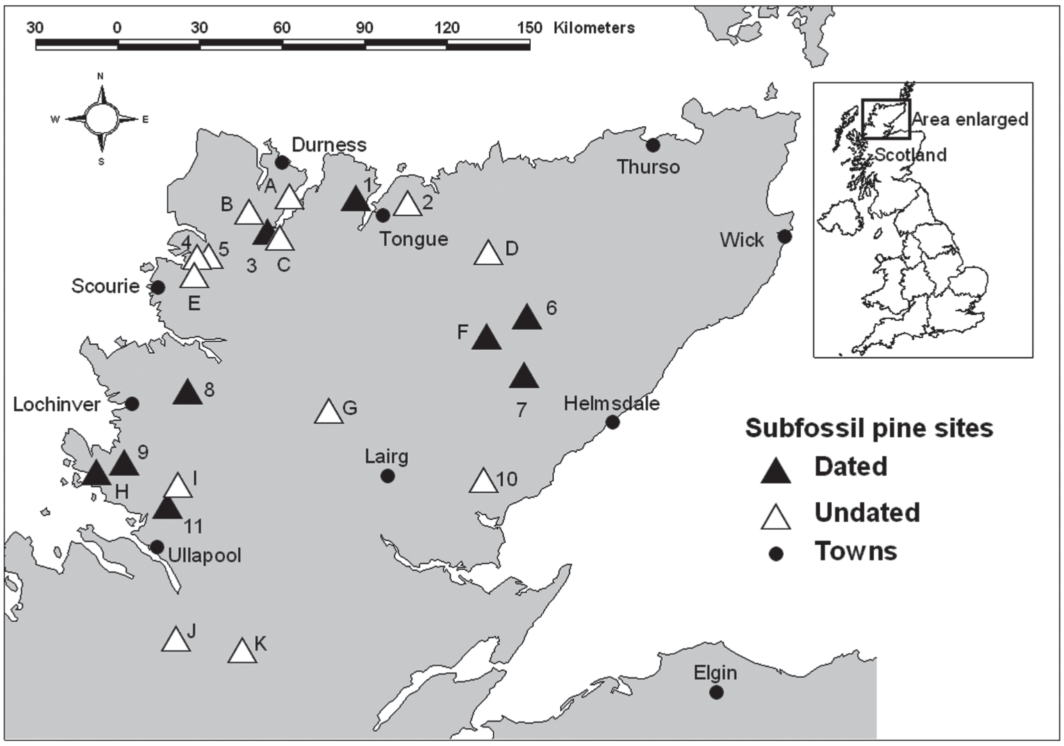

Figure 2. Map of Northern Scotland showing the locations of the main subfossil pine collections. 1–11 (new, this study), A–L (Daniell, 1997). See Table 1 for key to individual sites

Cross-matching

Three methods of cross-matching were used to ensure reliability: statistical tests, visual matching and replication. Cross-correlation algorithms were employed to search for the positions where tree-ring sequences correlated and possibly matched. The degree of affinity between tree-ring sequences is expressed by the Student's *t*-value (Baillie and Pilcher, 1973), using raw tree-ring measurements. Values of *t* in excess of 3.5 are quoted as significant and indicative of an acceptable position of match. Mean tree-ring series are calculated as the simple arithmetic mean of either the raw averaged tree measurement, or averaged site data.

Dendrochronological dating

A total of 134 subfossil pine stumps from eleven sites were sampled (Table 1 and Figure 2). Of these 20% contained less than 50 rings and were not measured, 54% could be cross-matched and 26% currently remain unmatched. Seven mean site chronologies containing a total of 49 individual series cross-matched to form a 386-year mean chronology called WRATH-7.

Initial attempts to calendar date the WRATH-7 chronology through cross-matching against existing Holocene oak (*Quercus* sp.) and *P. sylvestris* tree-ring chronologies developed by other workers in Europe failed (Cathy Groves, Hubert Leuschner and Samuli Helama, personal communication, 2008). Three mean site chronologies developed previously at Badanloch, Loch Shin and Loch Vatachan (Daniell, 1997) were made available to help increase replication. Narrow rings less than 0.20 mm/yr occurred near the ends of both the Loch Shin and Loch Vatachan chronologies; therefore to reduce the potential of missing rings the end 36 and 14 rings, respectively, were removed to establish two slightly shorter mean chronologies for these sites, named SHIN-ED and VATCH-ED. Narrow rings were also observed to occur near the beginning of the Badanloch chronology, and therefore the first seven rings were removed to establish a reference chronology named BADAN-ED. The two slightly shortened site chronologies for Badanloch and Loch Vatachan cross-match well with *t*-values of 8.27 and 5.57, respectively, against the WRATH-7 chronology. Nine site chronologies were therefore combined to form a mean regional chronology called WRATH-9 (Table 2).

Radiocarbon dating

Two samples of around 30 rings, taken from near the centres of subfossil pine from Strath Kanaid and Loch an Ruathair were AMS radiocarbon dated at the ^{14}CHRONO Centre (Queen's University of Belfast). Throughout this paper where only uncalibrated radiocarbon dates were available, the dates have been calibrated using OXCAL 4.0 (Bronk Ramsey, 2001). The 95.4% range of calibrated dates is rounded up to the nearest 50 years. From now on the use of BC will indicate calendar years before Christ.

Results

To further reduce the possible problem of missing rings, the WRATH-9 chronology was edited to a length replicated by three component site chronologies or more. This resulted in a 230 year long sequence called WRATH-9ED which spans rings 61–290 relative to the full WRATH-9 chronology. The WRATH-9ED chronology was found to produce significant matching with the first ring of the sequence at 3139 BC and the final ring of the sequence at 2910 BC (Table 3).

Table 1. Summary table of subfossil pine sites sampled and the tree-ring chronologies developed

Map Key	Site name	Altitude (m a.s.l)	Site Type	Mean depth of peat (m)	Mean sample height (m)	Trees Sampled	Cross-matched trees	Success rate	Mean cross-matching (*t*-value)	Layers of subfossil pine	Chronology name	MR	MS	AC	Mean Age	SD	Chronology length (yr.)	Oldest tree at site (yr.)	Short reference
1	An Dubh-loch	140	Valleyside mire	2.50	0.10	3	3	100%	5.24	1	DUBH-3	0.98	0.25	0.75	93	9	93	98	a
2	Loch Crocach	100	Valleyside mire	0.50	0.10	4	0	0%		1					138	47		204	a
3	Polla on Loch Eriboll	10	Valleyside mire	1.11	0.23	10	6	60%	4.69	2	POLL-6	0.71	0.18	0.79	248	69	344	354	a
4	Skerricha	40	Valleyside mire	0.72	0.01	11	7	64%	4.69	1	SKER-7	0.84	0.23	0.68	132	30	161	186	a
5	Loch na Thull	40	Valleyside Mire	0.53	0.04	3	0	0%		1					142	45		179	a
6	Loch an Ruathair	130	Valleyside mire	1.11	0.02	10	8	83%	3.62	2	RATH-8	0.86	0.20	0.78	191	37	232	243	a
				0.54	–0.05	2	2		8.15		RATH-B	1.23	0.25	0.85	134	47	102	167	a
7	Loch Ascaig	140	Valleyside mire	0.50	0.10	5	3	75%	5.54	1	ASCA-3	0.86	0.18	0.82	133	58	184	199	a
				0.50	0.10	3	3		5.16		ASCA-B	0.54	0.20	0.82	183	56	190	223	a
8	Loch Assynt	80	Valleyside mire	1.60	0.10	8	4	50%	3.26	1	ASSA-4	0.98	0.17	0.79	231	71	257	299	a
9	Druim Bad a' Ghaill	130	Watershed mire	0.62	–0.02	15	12	88%	4.10	1	BADA-12	0.96	0.20	0.66	156	28	186	196	a
				0.52	0.10	6	6		5.12		BADA-B	1.35	0.21	0.90	84	29	112	140	a
				0.43	0.00	3	3		4.65		BADA-C	1.62	0.19	0.65	87	14	102	100	a
10	Loch Farlary	220	Loch edge	2.50	0.00	6	3	50%		3	FARLY-3	0.96	0.22	0.79	131	33	154	368	a
11	Strath Kanaird	360	Spur mire	2.09	0.14	19	13	71%	3.43	1	SMUR-13	0.91	0.16	0.80	228	72	308	338	a
				1.12	0.05	2	2		5.88		SMUR-B	1.06	0.20	0.73	223	4	221	226	a
A	Loch Sian	50				1	0	0%										215	b
B	Srath Dionard	20	Peat erroded by river	1.00		10	5	50%				1.13	0.30	0.74	101			173	b
C	Loch Eriboll	10				2	0	0%											b
D	Lochstrathy	160	Forest road cutting			34	0	0%				0.63	0.30	0.72	60				c
E	Laxford Bridge	10	Peat cutting	0.65		12	9	75%				1.01	0.30	0.73	110			178	b
F	Badanloch	120	Reservoir edge			54	15	28%		2?	BADAN-ED	0.75	0.18	0.81	100		166	166	b + c
G	Loch Shin	90	Reservoir edge	0.50		29	19	66%			SHIN-ED	0.57	0.21	0.73	115		184	184	b
H	Loch Vatachan	20	Old peat cutting			27	20	74%			VATCH-ED	0.96	0.24	0.73	86		161	363	b
I	Knockanrock	210				2	0	0%											b
J	Fain	300				6	0	0%				0.54	0.29	0.78	184				b
K	Loch Glascarnoch	250	Reservoir edge	0.50		21	15	71%				0.61	0.29	0.75	154			232	b

Key: MR = mean ring width, MS = Mean sensitivity, AC = Auto correlation, SD = Standard deviation, a = This paper, b = Daniell 1997, c = Gear 1989

Table 2. Cross-matching between nine sub-fossil pine site mean chronologies combined to form WRATH-9. Dates in calendar years BC.

Filenames	Starts dates	End dates	VATCH	POLL	ASSA	BADA	RATH	ASCA	SMUR	DUBH
BADAN-ED	3148BC	2983BC	3.79	4.67	3.53	5.58	6.62	5.51	3.99	3.58
VATCH-ED	3159BC	2999BC		4.03	4.28	7.24	–	–	–	–
POLL-6	3175BC	2832BC			–	3.53	–	–	4.80	–
ASSA-4	3156BC	2900BC				5.03	–	–	3.70	4.33
BADA-12	3140BC	2955BC					4.33	–	4.44	4.12
RATH-8	3139BC	2908BC						5.22	6.23	–
ASCA-3	3137BC	2954BC							4.63	–
SMUR-13	3097BC	2790BC								3.7
DUBH-3	3095BC	3003BC								

KEY: cross-matching *t*-values (Baillie and Pilcher 1973).

Table 3. Cross-matching between the WRATH-9ED chronology and reference chronologies. The PINE3000 chronology contains one tree from Sluggan Moss, eight trees from Ballymacombs More and nine trees from Sharvogues. Dates in calendar years BC

Filenames	Start dates	End dates	*t*-value	Location & Short reference
PINE3000	3177BC	2642BC	5.70	Mean Irish pine chronology (D Brown 2007, pers. comm.)
SHARVOG1	3177BC	2642BC	4.56	Shavogues - N. Ireland (Pilcher et al. 1995)
BALLYMC5	3138BC	2766BC	3.88	Ballymacombs More - N. Ireland (D Brown 2007, pers. comm.)
GARRYBOG	3418BC	2952BC	3.85	Garry Bog - N. Ireland (Brown 1991)
BALLYMC3	3147BC	2630BC	3.81	Ballymacombs More - N. Ireland (D Brown 2007, pers. comm.)

Confirmation of the dating of the WRATH-9ED chronology was sought by ^{14}C dates. Dates for two samples cross-matched within the chronology were combined with three previous ^{14}C dates (Daniell, 1997). These five dates (Table 4) were wiggle matched to span 3029–2936 cal. BC. The dendrochronological dates identified for the start and end of the same sequence is 3104–3008 BC (a difference of just 75 years) and considered consistent with the provisional dendrochronological dating of this chronology.

Growth trends and morphology

The mean ring-width for the WRATH-9 chronology is 0.87 mm/yr. This was surprisingly uniform as few trees showed the gradual reduction of ring-width normally associated with age. Just two 20-year periods between 3110–3090 and 3040–3020 BC are identified during which mean decadal growth rate exceeded 1.00 mm/yr (Figure 3: vertical bars A and B). Three decades of particularly low decadal growth rates (<0.60 mm/yr) are common between the majority of the chronologies, and which coincide with dying-off phases between 3000–2990, 2960–2950 and 2910–2900 BC (Figure 3: vertical bars C, D and E). The mean stump height from six sites was 31 cm and mean root depth from 5 sites was 0.49 cm (Table 5). *In situ* stumps were in vertical position; the roots recorded at all sites were of shallow 'I' girder form. Upward bending adventive roots were observed at Loch Ruathair.

Characteristics of a pine expansion and demise

The cohort of pine dated from the nine sites (Figure 3) indicates a rapid, widespread and brief expansion of Scots pine across the peatlands of northern Scotland, which may be summarised as follows:

- germination at the three earliest sites (which extend over a 50 km section along the west coast of Scotland) probably occurred simultaneously around 3200 BC
- initial germination at all nine cross-matched sites occurred within a brief 100 year period, between about 3200 and 3100 BC
- two periods of high decadal growth (> 1 mm/yr) between 3110 and 3090 BC and 3040 and 3020 BC and continued germinations indicate that conditions favourable for the growth of pine on peat existed for a 200 year period between about 3200 and 3000 BC
- decreases in decadal growth rates (<0.6 mm/yr), an absence of germination and the dying-off of 73% of trees over a 100 year period indicate that conditions less favourable for the growth of pine on peat returned between about 3000 and 2900 BC
- a remnant population of just six trees at three sites survived 360 years after the first phase of identified germination
- pine is shown to have survived for only a single generation at all nine sites.

Table 4. The relative positions of ^{14}C dated samples in the WRATH-9 chronology

Location	14C code	C14 date	S.D.	cal. BC 2σ range start	cal. BC 2σ range end	Start ring	End ring
Loch Vatachan	SRR-5814	4570	45	3500	3100	78	114
Loch Raithair	UBA-8470	4409	32	3350	2900	120	140
Badanloch	SRR-3566	4405	50	3350	2900	141	191
Badanloch	SRR-3567	4370	50	3350	2850	170	200
Strath Kanaird	UBA-8469	4335	31	3050	2850	182	202

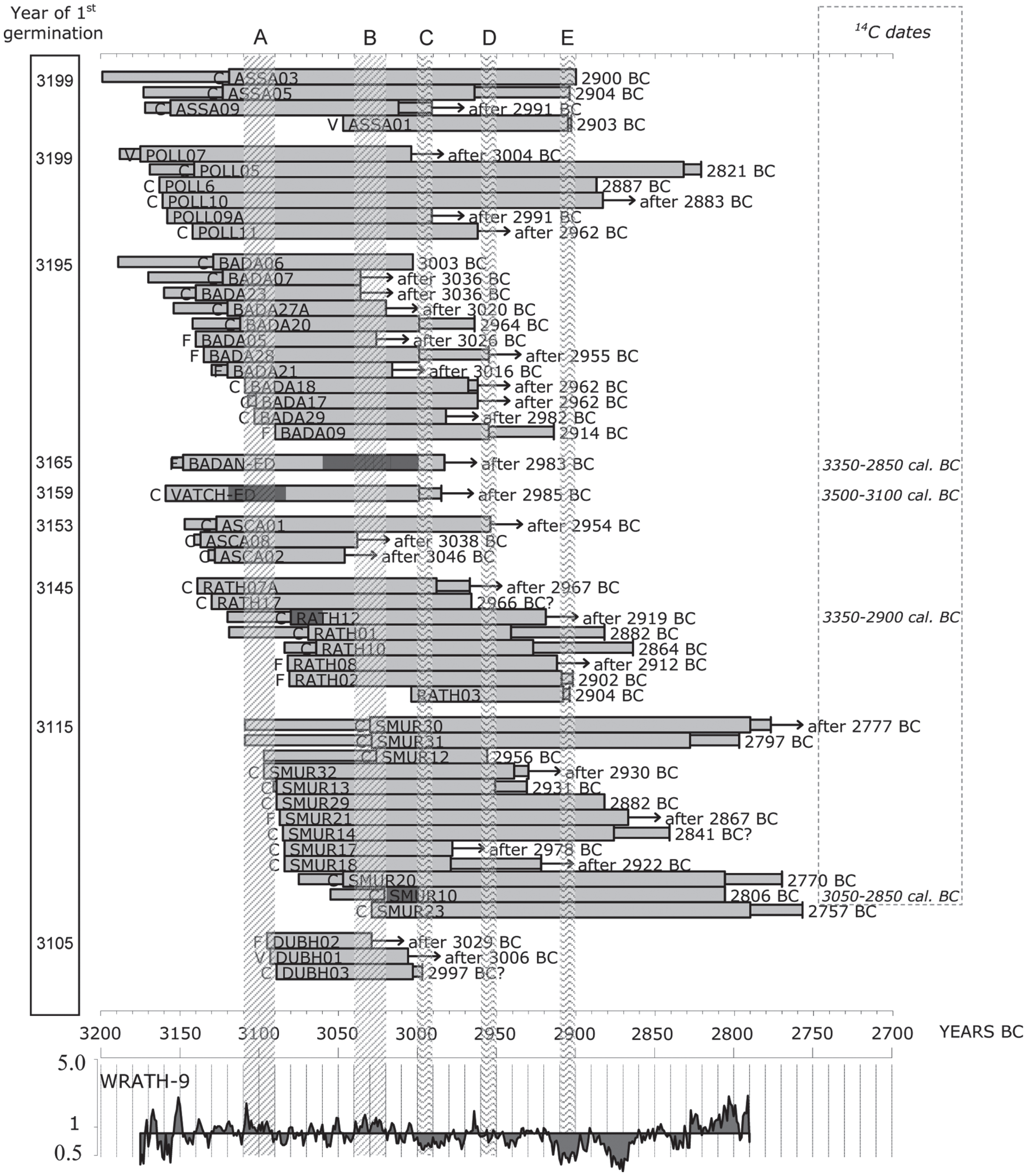

Figure 3. Top: Bar diagram showing the span of tree-ring sequences cross-matched in the WRATH-9 master chronology. C, pith; V, within five rings of pith; F, within 10 years of pith. The narrower horizontal bars identify approximated ring counted sections of the chronologies. Diagonal hatched vertical bars highlight periods common between sites of high germination and relatively high radial growth rate (A), and relatively high radial growth rate (B). Wave hatched vertical bars highlight common phases of relatively low radial growth rate and dying-off (C to E). Dark grey horizontal bars indicate the position of ^{14}C dated sections, these dates are shown on the right (see Table 1 for key to samples' site codes). Bottom: Plot of ring width (mm) is plotted on a logarithmic y-axis

Discussion

Despite the relatively low number of samples dated from each site, the nine sites provide good evidence for regional synchronicities in the germination, changes in radial growth rates and dying-off. These changes in this cohort of dated pine are interpreted as climatically induced and probably related to changes in the water-table of bogs.

Table 5. Information recorded from cross-matched Scots pine stumps in Scotland

Site	Number of samples dated	Mean stump height (m)	Mean root depth (m)	% samples with bark	Number of samples where root data was recorded
An Dubh-loch	3	?	?	33%	0
Drium Bad a'Ghaill	12	0.12	0.43	25%	7
Loch an Ruathair	8	0.24	0.57	63%	5
Loch Ascaig	3	0.40	0.50	33%	1
Loch Assynt	4	0.33	0.46	75%	4
Polla on Loch Eriboll	6	0.44	?	63%	0
Strath Kanaird	13	0.32	0.50	69%	2

Inferred lower water-table (3200–3000 BC)

A first indicator of a low water-table on bogs is the recruitment of pine onto their surface. Bogs are entirely dependent upon waterlogging, whether sustained or intermittent, for their development and growth. Even if pine is present on drier soils near the margins of a bog, any seeds blown onto a waterlogged surface do not germinate (McVean, 1963). As a result, the germination of pine across a wide region must indicate a fall in a bog's water-table before germination could occur. The germination of pine occurred almost simultaneously at three sites around 3200 BC and was followed quickly at four other sites between 3165 and 3145 BC. Close coincidence between the start of the Scottish, as well as some Irish pine chronologies (Figure 4), shows how widespread this phase of germination and subsequent successful growth was, and is consistent with a climatic trigger.

Higher decadal growth rates are suggested as a second indicator of low water-table where pine grows on bogs. Studies on modern pine show its growth, and indeed survival, on bogs to be strongly dependent on a low water-table (Boggie, 1972; Laine *et al*., 1995; Legg *et al.*, 2003). Two periods of a widespread increase in growth rate, between 3110–3090 BC and 3040–3020 BC, are consistent with a low water-table. Furthermore, the first period coincides with the initial germination of pine at both the highest and most northerly sites sampled, as well as germination at other sites, which reinforces a link with a lowering of water-table. Unambiguous evidence for a widespread occurrence of drier conditions at this time comes from the largest peak of Irish bog oak and lake-edge tree populations at 3050 BC (Turney *et al.*, 2006). Also as far as Germany, Leuschner *et al.* (2007) identify a pine germination phase between 3040 and 3020 BC which coincides precisely with the second period of high decadal growth identified in our data. Few bog surface wetness records extend before 2000 cal. BC in northern Britain; nevertheless correlative short dry shifts are shown between 3250 and 3050 cal. BC (Anderson *et al.*, 1998) and 3050 and 2650 cal. BC (Langdon and Barber, 2003).

The depth of roots where pine grows on peat provides a third indicator of a lower water-table. Studies on modern pine by Köstler *et al*. (1968) and McHaffie *et al.* (2002) show the depth of pine roots in bog corresponds closely to the level of the water-table. Our data (Table 5) show a mean rooting depth of 50 cm and maximum of 80 cm, which indicate a low water-table. However, the absence of tap roots and the occurrence of 'I' girder roots provide strong evidence that the water-table was rarely far below the surface. These results are broadly consistent with quantitative water-table reconstructions for the late Holocene from a raised bog in Finland which show that water-table depth varied between 2.5 and 38 cm (Väliranta *et al.*, 2007). Whereas, in northern Britain between

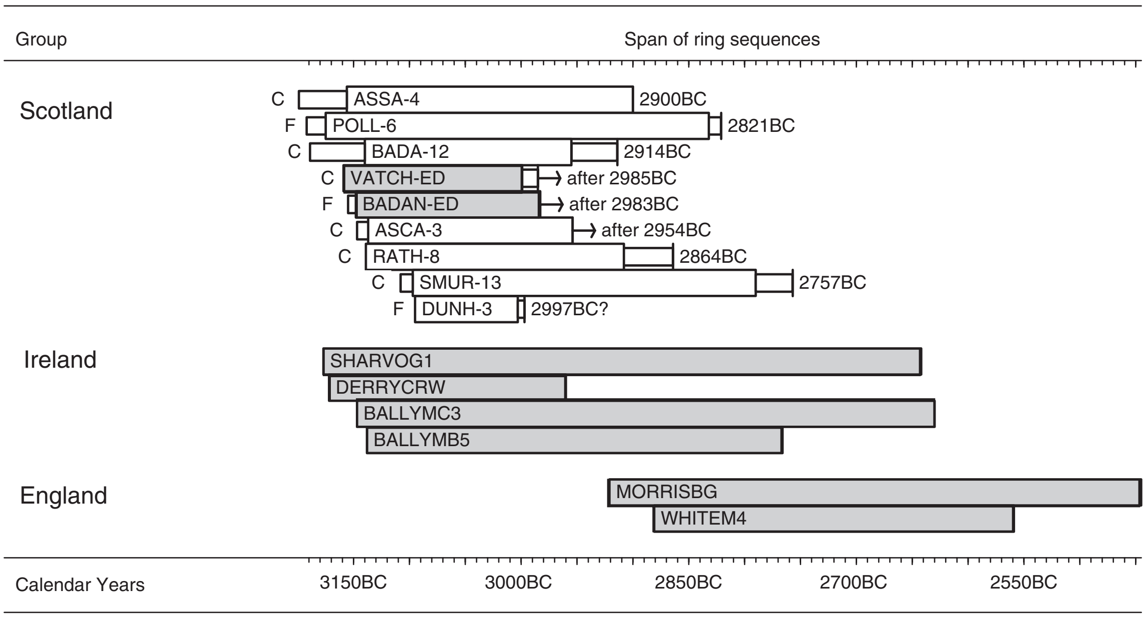

Figure 4. Bar diagram showing relative positions of pine chronologies in the British Isles. C, pith; V, within five rings of pith; F, within 10 years of pith. The narrower bars identify approximated ring counted sections of the chronologies. The dying-off date of the last tree sampled is indicated with the chronologies from Scotland. Grey bars indicate chronologies developed by other workers or outside Scotland: VATCH-ED and BADAN-ED (edited from Daniell, 1997), SHARVOG1 (D. Brown, unpublished data, 2007), DERRYCRW (quoted in Lageard *et al.*, 1999), BALLYMC3 and BALLYMB5 (McNally and Doyle, 1984), MORRISBG (Boswijk and Whitehouse, 2002) and WHITEMOSS (Chambers *et al.*, 1997).

2000 cal. BC and the present day, the maximal lower limit of reconstructed water-table extended to just 16 cm below the surface (Charman *et al.*, 2006).

Inferred rise in water-table (from around 3000 BC)

Once established on bog, pine cover itself is expected to reduce a water-table level through evapotranspiration and improve the nutrient status of bog by increasing decomposition of peat through aeration, as well as by litterfall through trapping nutrients from the atmosphere. However, our data show conditions favourable for the survival of pines on bog lasted less than their natural lifespan. The two oldest subfossil pine identified in this analysis are 354 and 338 years old from Polla on Loch Eriboll and Strath Canaird, respectively. The oldest tree at Loch Vatachan was 363 years old (Daniell, 1997). In Scotland, Scots pine on soil show its potential to live for more than 450 years (Bartholomew *et al.*, 2001; Grace and Norton 1990), but on bog ages over 350 years are rarely achieved, probably because of waterlogging.

Evidence for a rise in water-table is shown by adventive roots, which are an important morphological feature of pine, although their significance was not recognised at the time of sampling. Leuschner *et al.* (2007) attribute the formation of this form of root to growth following a moving aerated surface of the bog. One upward-bending adventive root was observed in a photo from one of our sites, which is indicative of a rise in water-table during the lifetime of the tree. It is likely that adventive roots may have gone unnoticed at the other sampled sites.

Decades of particularly low ring-width in pine growing on peat are likely to reflect a rise of water-table. Most tree species barely survive when ring-width is reduced to below 0.50 mm/yr (White, 1998). Decades of such low ring-width occur infrequently in the mean site chronologies presented here and coincide with the dying-off of pine. An advantage of this research over many studies is the recovery of *in situ* samples, often with bark, from a wide 60 km^2 area, which provides precise information on both the timing of germination and tree death. Subfossil trees commonly recovered from lakes and other contexts are not *in situ*, the trunk/root interface is often absent and the outermost rings have usually decayed (Zetterberg *et al.*, 1994; Eronen *et al.* 2002). Therefore, the phases of germination and dying-off may be missed.

Synchronicity between decades of low ring-width and dying-off in our pine implies a climatic mechanism causing environmental stress between 3000–2990, 2960–2950 and 2910–2900 BC, which we attribute here to successive elevations of water-table. This mechanism has been observed in pine preserved in peat at White Moss in the NW of England (Lageard *et al.*, 1999), where decadal reductions in ring-width and dying-off phases occur between 2800–2790, 2750–2740 and 2700–2680 BC. Pine at Campemoor in Germany also show dying off in 2960 BC and between 2880–2870 and 2780–2730 BC (Leuschner *et al.*, 2007). Comparisons between the pine and pollen/spore records near both these sites suggest successive episodes of elevated water-table that caused the dying off of pine. Pine dying-off because of increased waterlogging has also been interpreted at Hatfield Moors in the East Midlands of England, where *Pinus*-heath woodland growing between 2921 and 2445 BC was subsequently overgrown by peat (Boswijk and Whitehouse, 2002). In addition, present-day observations of mire-rooted pine provide additional evidence that elevations in water-table can cause dying-off in cohorts of trees within decadal timescales (Lageard *et al.*, 1999).

Taphonomy

The preservation of subfossil pine itself within peat provides strong evidence for a rise in water-table associated with dying-off, as anaerobic/waterlogged conditions are necessary to prevent decay. Peat accumulation is dependent on waterlogged conditions preventing complete decomposition of organic matter, as seen in the high correlation between increasing water and increased peat growth (Barber, 1981). In this study bark was found to be prone to loss from our samples once dried. Both the good preservation of bark and height of stumps preserved above the surface of peat the tree germinated on, suggest rapid peat accumulation and presumably waterlogging after death. Tallis and Switsur (1983) also conclude that distribution of tree remains coincides with periods of faster peat accumulation.

The full WRATH-9 chronology spans about 3175–2790 BC, but few samples extend after 2840 BC and so little discussion is made beyond that date. The last of the cohort of pine germinated in 3029 BC and died in 2757 BC. Our data suggest that in Scotland conditions for preservation of pine existed between 3029 and 2757 BC, and during this period germination was absent. Both these factors are indicative of a high water-table. Wider afield in Ireland, the long Belfast bog oak chronology shows distinct decades of very low growth starting in 2850 BC and 2750 BC. A general reduction in the frequency of bog oaks in Ireland between 2600 and 2400 BC supports the idea that bogs became wetter at this time (Pilcher, 1990). The youngest trees sampled at Sluggan Bog and Garry Bog stopped growing in 2642 and 2569 BC, respectively (Brown, 1991 in Hall *et al.*, 1994). A long bog oak chronology, developed in lower Saxony in Northern Germany, shows two large-scale growth depressions at 2950–2850 and at 2780–2705 BC, which reflect change towards wetter conditions at these times (Leuschner *et al.*, 2002).

A climatic mechanism for pine's expansion and demise

Godwin (1956) suggested that Scots pine on the surface of bogs may have become denser during dry climatic periods and have declined as wetter climate returned. Synchronous changes across a region have been interpreted as abrupt shifts in climate. Schoning *et al*. (2005) support the hypothesis that water-table changes in bogs in some areas are driven by climate. Charman (2007) using a high-resolution record of reconstructed water-table changes in relation to instrumental weather record concluded: in oceanic regions with rainfall distributed throughout the year and relatively low summer temperatures, rainfall is the primary driver of peatland water-tables. The change from relatively dry to wet conditions is proposed as a trigger for bog suffocating and preserving subfossil pine horizons.

Our results are consistent with a prevailing high water-table on bogs in northern Scotland discouraging pine growth. A mechanism whereby the lowering of the water-table brought about by climate change allows the growth of pines, which then subsequently died and became preserved as climatic conditions favourable to bog growth return, is suggested. The cessation of pine germination on peatland around 3000 BC coincides with a deterioration of growth conditions and increased mortality, reinforcing the premise that conditions of peat accumulation that preserves pine also prevent tree colonization. Few published records have the chronological precision afforded from our data. However, around this time a similar rapid and brief (probably single generation) expansion of Scots pine, associated with a short surface drying of bogs, occurs in particularly oceanic areas of the British Isles (Caseldine *et al.*, 2005; Charman, 1994; Mighall *et al.*, 2004; Tipping *et al.*, 2008). Interestingly, the widespread preservation of a pine horizon from 3000 BC also coincides with a hydroclimatic 'system switch' at 3000 cal. BC interpreted from an increase in frequency and severity of floods from 506 radiocarbon dated fluvial units in Great Britain (Macklin *et al.*, 2005).

The survival of six pine trees beyond 2840 BC shows the potential for pine to survive at minimal growth rates on bog, well after probable climatic deterioration. This highlights a problem of a blurred boundary, when trying to identify climatic deterioration from the analysis of *Pinus* pollen. Our data suggest the rapid expansion of pine onto bogs across northern Scotland could be a more accurate dating target than the general loss of pinewoods around 2500 cal. BC, i.e. the 'pine decline'. Other workers in the region have found startling increases in *Pinus* pollen well above Bennett's (1984) figure of 20% total land pollen for 'local' pine forest, over just a few centimetres (Charman, 1994; Daniell, 1997). Dendrochronological dating of subfossil pine further south in England (Boswijk and Whitehouse, 2002; Chambers *et al*., 1997; Lageard *et al*., 1999) indicate germinations of pine after the main dying-off phase and inferred rise in water-table we identified. However, marked differences in past climate have been shown even between northern and southern Scotland (Langdon and Barber, 2004, 2005) and the more southern location or type of bog may account for the differences. Leuschner *et al*. (2007) also suggest that the opening up of the canopy may produce a phase of germination in a light-demanding species such as Scots pine, which could be a factor in the more southern locations where competition with oak can occur.

Future research

From our data and other raised bog sites of subfossil pine currently known in Scotland, it is unlikely that long (> 1000 yr) chronologies such as for oak in Ireland and Western Europe can be developed. Although as yet, the dendrochronological potential of subfossil pine, that may have fallen into lochs, remains largely unexplored. In Ireland only raised bogs have been found to consistently produce timber of satisfactory quality for dendrochronology (Pilcher *et al.*, 1995). Nevertheless, our results suggest the potential to extend a network of >250 yr long pine chronologies in northern Scotland is excellent, and it is likely that this network can be extended to Ireland. The mean cluster of radiocarbon dates of an extensive horizon of subfossil pine in North Mayo dating to 3100–2600 cal. BC is indistinguishable from a mean of 3050–2550 cal. BC calculated from subfossil pine in northern Scotland (Caulfield *et al.*, 1998). Pines dated between 3700 and 2600 cal. BC at Cadogan's Bog (Mighall *et al.*, 2004) suggest the same horizon extends to the southwest of Ireland.

Precisely why the full WRATH-9 chronology should currently fail to cross-match against reference chronologies is unclear, but three main reasons (which are not mutually exclusive) related to pine growth on peat are considered:

(1) missing rings in the first and last 50 years of pine growth may occur in some of the less well replicated component chronologies
(2) a strong regional response of pine to climate may be limited to periods with a lower water-table
(3) variation in water level over a single bog (or between bog types) might lead to different delays or different response of pine at different locations.

Missing rings in subfossil pine have previously been reported (Bridge *et al.*, 1990; Gunnarson, 1999; Lageard *et al.*, 1999; Pilcher *et al.*, 1995) and low correlation between sequences have similarly been attributed to this problem (Bridge *et al.*, 1990; Mighall *et al.*, 2004; Pilcher *et al.*, 1995). The discrepancy between WRATH-9 and a mean Irish pine chronology PINE3000 (D. Brown, unpublished data, 2007), occurs at a sharp reduction in growth in the latter chronology in 2910 BC (Figure 5) and missing rings are considered likely to occur at this point. Because of this the WRATH-9ED chronology is provisionally dated and increased replication over this period is required to resolve this issue. However, assuming the first two points are valid, taking them into account could increase the potential of dating future subfossil material and suggests re-examination of earlier researcher's tree-ring series might also enable dating.

As ^{14}C dates for subfossil pine in the north of Scotland suggested a single broadly coeval horizon, the identification of a second lower horizon of pine at two sites (see Table 1) was unexpected. Gear (1989) suggests Badanloch and a locality near Syre (NGR: NC669445) also contained two layers of pine. Subfossil evidence of this earlier expansion of pine extending beyond the current treeline appears to have previously been missed and may explain the failure of some of our samples to cross-match. Existing radiocarbon dates from subfossil material in the British Isles, indicate a bimodal peak of pine occurrence (Bridge *et al.*, 1990; Caulfield *et al.*, 1998; Mighall *et al.*, 2004; Tallis and Switsur, 1983; Wilkins, 1984). These peaks correspond broadly with two wet periods between 5200–4700 and 2900–2350 cal. BC, identified by deuterium isotope ratios in pine stumps from the Cairngorms (Dubois and Ferguson, 1985). Although the D:H ratios do not necessarily define periods of increased precipitation, the second period closely corresponds with a rise in water-table inferred from our data and the majority of subfossil pine dendrochronologically dated in the British Isles today. A second lower horizon of pine has also been recorded in more southerly locations and radiocarbon dates indicate that this horizon may be broadly coeval. This suggests the potential to date and elucidate an earlier Holocene climate shift through the tree-ring analysis of subfossil pine.

Numerous studies have shown the dendroclimatological response of modern pine that grows on mineral substrate to climate at the upper tree limit, for a review see Schweingruber (1996), but much less is currently understood about this relationship where pine grows on peat. Few studies have examined the relationship between subfossil pine and pollen records at the same location. Combining dendrochronological analysis with more recent high-resolution hydrological studies on bog systems (e.g. Charman, 2007; Väliranta et al., 2007) may establish clear relationships between stump height, accumulation rates, root depth and water levels, as well as enabling a more accurate quantitative prediction of the effects of climate change. It is likely that certain types of

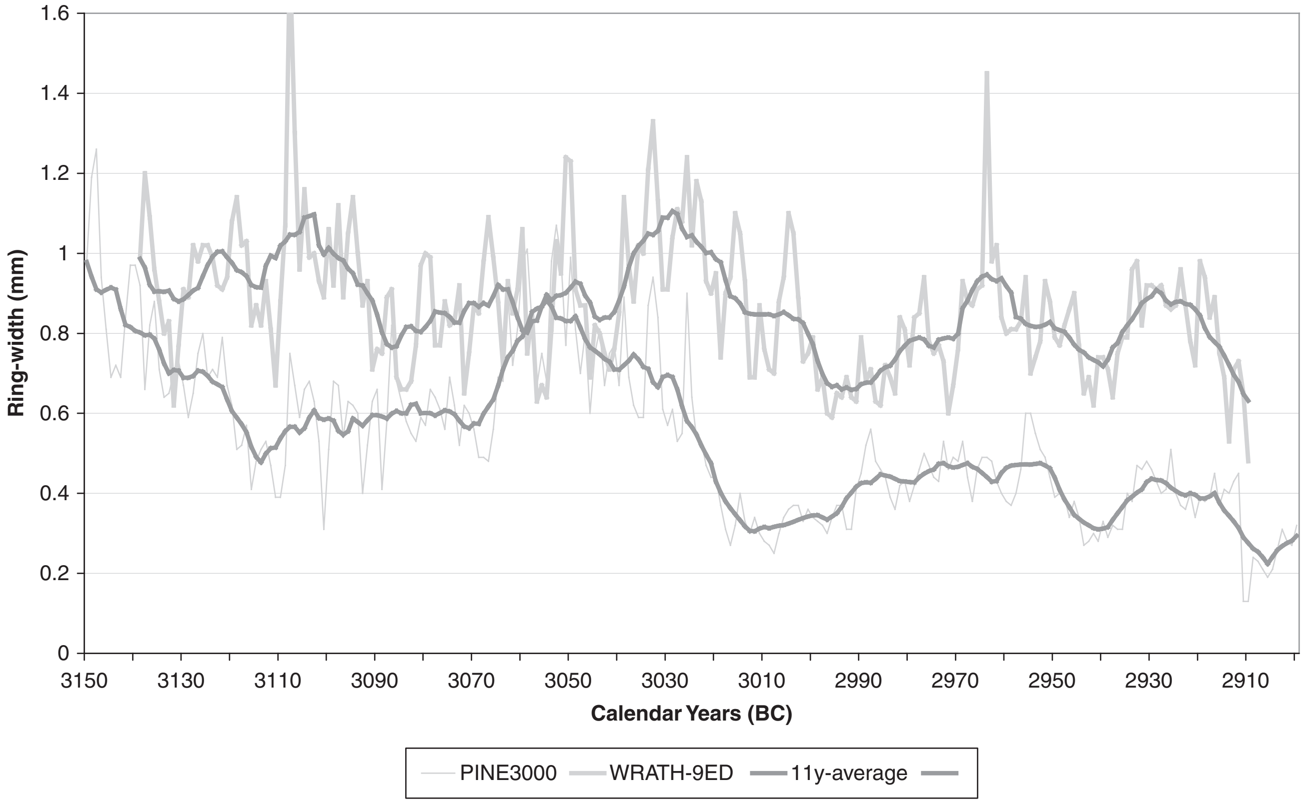

Figure 5. Ring-width plot of sequences WRATH-9ED (upper) and PINE3000 edited to span 3150–2900 BC (lower), which cross-match together with a *t*-value of 5.7. Similarities in the patterns of variation at both high and medium frequencies can be seen

bogs are more sensitive to climatic fluctuations than others, as precipitation/evaporation varies with different topography and drainage. The peatlands of Scotland may be particularly suitable for such studies, being more sensitive to changes in effective humidity than the more continental areas of Europe (Barber *et al.*, 2004; Väliranta *et al.*, 2007).

Conclusions

A regionally extensive horizon of *in situ* subfossil Scots pine is cross-matched and provisionally dated to form the first calendar-dated Neolithic pine chronology for northern Scotland (WRATH-9ED) which spans 3139–2910 BC. This stratigraphic marker (and potentially a second, earlier one) highlights the potential to reconstruct the inter- and intraregional response of Holocene pine to climate change and other environmental stress at annual resolution.

Synchronous patterns of ring-width variations and population dynamics from bog pine over a wide area support the hypothesis that the ecological and hydrological changes were triggered by climate change. Pine appearance on bog coincides with a short period of relatively dry conditions also identifiable from independent palaeohydrological analysis, and the dying-off and preservation of pine with a return to wet conditions. The broadly common changes in site wetness inferred at sites over the region provide strong evidence that these changes are related to regional climate change, rather than simply the result of local site changes. Our results indicate that climatically induced changes in water-table was probably the primary control on the germination, growth rates and dying-off of bog pine across northern Scotland between 3200 and 2900 BC.

The results do not support the theory that pine in northern Scotland died by a brief cataclysm. They indicate the pine decline identified through palynological evidence to be an imprecise target for the timing of climatic change. The evidence is consistent with Holocene pine trees in northern Scotland being near a critical ecological threshold and supports the hypothesis advanced by Gear and Huntley (1991) who proposed that regional climate changes ultimately caused both the initial expansion of pine into the far north of Scotland and its subsequent decline and eventual demise.

Acknowledgements

This research was carried out as part of a PhD research project carried out by AM at Brunel University. It was funded by Tree-Ring Services and a grant towards fieldwork by the Quaternary Research Association. We are grateful for permission from landowners to carry out sampling and to John Daniell for kind access to tree-ring data. The authors are also grateful to the reviewers Richard Tipping and Andrew Haggart for their thoughtful and helpful comments which improved this manuscript.

References

Anderson DE, Binney HA and Smith MA (1998) Evidence for abrupt climatic change in northern Scotland between 3900 and 3500 calendar years BP. *The Holocene* 8: 97–103.

Anonymous (1964) Liability of trees on peat to wind-throw. *Scottish Forestry* 18: 38–43.

Baillie MGL (1990) Checking back on an assemblage of published radiocarbon dates. *Radiocarbon* 32: 361–366.

Baillie MGL, Pilcher JR (1973) A simple cross-dating program for tree-ring research. *Tree-ring Bulletin* 33: 7–14.

Barber KE (1981) *Peat Stratigraphy and Climatic Change: A Palaeoecological Test of the Theory of Cyclic Peat Bog Regeneration*. Balkema.

Barber KE, Zolitschka B, Tarasov P and Lotter AF (2004) Atlantic to Urals – the Holocene climatic records of Mid-Latitude Europe. In: Battarbee RW, Gasse F and Stickley CE (eds) *Past Climate Variability Through Europe and Africa*. Developments in Paleoenvironmental Research 6, Springer.

Bartholomew A, Malcolm DC and Nixon CJ (2001) The Scots pine population at Glen Loyne, Invernesshire: Present condition and regenerative capacity. *Scottish Forestry* 55: 141–148.

Bell M, Walker MJC (2005) *Late Quaternary Environmental Change – Physical and Human Perspectives*. Pearson.

Bennett KD (1984) The post-glacial history of *Pinus sylvestris* in the British Isles. *Quaternary Science Reviews* 3: 133–155.

Bennett KD (2005) Map of distribution of Scottish pine remains. Public communication. Retrieved 18 December 2006 from http://www.kv.geo.uu.se/scotland/pine_map.html

Birks HH (1975) Studies in the vegetational history of Scotland. IV. Pine stumps in Scottish blanket peats. *Philosophical Transactions of the Royal Society of London B* 270: 181–226.

Boggie R (1972) Effect on water-table height on root development of *Pinus contorta* on deep peat in Scotland. *Oikos* 23: 304–312.

Boswijk G, Whitehouse NJ (2002) *Pinus* and *Prostomis*: A dendrochronological and palaeoentomological study of a mid-Holocene woodland in eastern England. *The Holocene* 12: 585–596.

Bridge MC, Haggart BA and Lowe JJ (1990) The history and palaeoclimatic significance of subfossil remains of *Pinus sylvestris* in blanket peats from Scotland. *Journal of Ecology* 78: 77–99.

Bronk Ramsey C (2001) Development of the radiocarbon calibration program OxCal. *Radiocarbon* 43: 355–363.

Brown DM (1991) Studies on *Pinus sylvestris* L. from Garry Bog, Co. Antrim. Unpublished M.Sc. thesis, Queen's University Belfast.

Carlisle A, Brown A (1968) Biological flora of the British Isles. *Pinus sylvestris* L. *Journal of Ecology* 56: 269–307.

Caseldine C, Thompsen G Langdon C and Hendon D (2005) Evidence for an extreme climatic event on Achill Island, Co. Mayo, Ireland around 5200–5100 cal. yr BP. *Journal of Quaternary Science* 20: 169–178.

Caulfield S, O'Donnell RG and Mitchell PI (1998) ^{14}C dating of a Neolithic field system at Céide Fields, Country Mayo, Ireland. *Radiocarbon* 40: 629–640.

Chambers FM, Lageard JGA, Boswijk G, Thomas PA, Edwards KJ and Hillam J (1997) Dating prehistoric bog-fires in northern England to calendar years by long-distance cross-matching of pine chronologies. *Journal of Quaternary Science* 12: 253–256.

Charman DJ (1994) Late-glacial and Holocene vegetation history of the flow country, Northern Scotland. *New Phytologist* 127: 155–168.

Charman DJ (2007) Summer water deficit variability controls on peatland water-table changes: Implications for Holocene palaeoclimate reconstructions. *The Holocene* 17: 217–227.

Charman DJ, Garnett MH (2005) Chronologies for recent peat deposits using wiggle matched radiocarbon ages: problems with old carbon contamination. *Radiocarbon* 47: 135–145.

Charman DJ, Blundell A, Chiverrell RC, Hendon D and Langdon PG (2006) Compilation of non-annually resolved Holocene proxy climate records: Stacked Holocene peatland palaeo-water table reconstructions from northern Britain. *Quaternary Science Reviews* 55: 336–350.

Daniell JRG (1997) The late-Holocene palaeoecology of Scots pine (*Pinus sylvestris* L.) in north-west Scotland. Unpublished Ph.D. Thesis, Durham University.

Dubois AD, Ferguson DK (1985) The climatic history of pine in the Cairngorms based on radiocarbon dates and stable isotope analysis, with an account of the events leading up to its colonisation. *Review of Palaeobotany and Palynology* 46: 55–80.

Ennos RA (1991) Genetic variation in Caledonian pine populations: Origins, exploitation and conservation. In: Muller-Starch G, Ziehe M (eds) *Genetic Variation in European Populations of Forest Trees*. Sauerlander's Verlag, 235–249.

Eronen M, Zetterberg P, Briffa KR, Linderholm HW, Meriläinen J and Timonen M (2002) The supra-long Scots pine tree-ring record for Finnish Lapland: Part 1, chronology construction and initial references. *The Holocene* 12: 673–680.

Froyd CA (2005) Fossil stomata reveal early pine presence in Scotland: Implications for Postglacial colonization analysis. *Ecology* 86: 579–586.

Gear AJ (1989) Holocene vegetation history and the palaeoecology of *Pinus sylvestris* in northern Scotland. Unpublished Ph.D. Thesis, University of Durham.

Gear AJ, Huntley B (1991) Rapid changes in the range limits of Scots pine 4000 years ago. *Science* 251: 544–547.

Godwin H (1956) *The History of the British Flora*. Cambridge University Press.

Grace J, Norton DA (1990) Climate and growth of *Pinus sylvestris* at its upper altitudinal limit in Scotland: Evidence from tree growth-rings. *Journal of Biogeography* 78: 601–610.

Gunnarson BE (1999) A 200-year tree-ring chronology of pine from a raised bog in Sweden: Implication for climate change? *Geografiska Annaler Series A-Physical Geography* 81A: 421–430.

Hall VA, Pilcher JR and McCormac FG (1994) Icelandic volcanic ash and the mid-Holocene Scots pine (*Pinus sylvestris*) decline in the north of Ireland: No correlation. *The Holocene* 41: 79–83.

Hughes MK (1987) Dendroclimatology of *Pinus sylvestris* L. in the Scottish Highlands. In: Ward RGW (ed). *Applications of Tree-ring Studies: Current Research in Dendrochronology and Related Subjects*. BAR International Series, 333.

Huntley B, Daniell JRG and Allen JRM (1997) Scottish vegetation history: the Highlands. *Botanical Journal of Scotland* 49: 163–176.

Köstler JN, Brückner E and Bibelriether H (1968) *Die Wurselm der Waldbäume*. Parey.

Lageard JGA, Chambers FM and Thomas PA (1999) Climatic significance of the marginalization of Scots pine (*Pinus sylvestris* L.) *c*. 2500 BC at White Moss, South Cheshire, UK. *The Holocene* 9: 321–331.

Lähde E (1969) Biological activity in some natural and drained peat soils with special reference to oxidation-reduction conditions. *Acta Forestalia Fennica* 94: 1–69.

Laine J, Vasander H and Sallantaus T (1995) Ecological effects of peatland drainage for forestry. *Environmental Reviews* 3: 286–303.

Langdon PG, Barber KE (2003) A 7500-year peat based palaeoclimatic reconstruction and evidence for a 1100-year cyclicity in bog surface wetness from Temple Hill Moss, Pentland Hills, SE Scotland. *Quaternary Science Reviews* 22: 259–274.

Langdon PG, Barber KE (2004) Snapshots in time: Precise correlations of peat-based proxy climate records in Scotland using mid-Holocene tephras. *The Holocene* 14: 21–33.

Langdon PG, Barber KE (2005) The climate of Scotland over the last 5000 years inferred from multiproxy peatland records: Intersite correlations and regional variability. *Journal of Quaternary Science* 20: 549–566.

Legg CJ, McHaffie H, Amphlett A and Worrell R (2003) The status of wooded bogs at Abernethy, Strathspey. In: *Restoring Natural Forest Habitats*. Conference Proceedings. Munlochy, 12-16.

Leuschner H-H, Sass-Klaassen U, Jansen E, Baillie MGL and Spurk M (2002) Subfossil European bog oak: Population dynamics and long-term growth depressions as indicators of changes in the Holocene hydro-regime and climate. *The Holocene* 12: 695–706.

Leuschner H-H, Bauerochse A and Metzler A (2007) Environmental change, bog history and human impact around 2900 B.C. in NW Germany – preliminary results from dendroecological study of a sub-fossil pine woodland at Campemoor, Dümmer Basin. *Vegetation History and Archaeobotany* 16: 183–195.

Lindsay RA (1995) *Bogs: The Ecology, Classification and Conservation of Ombrotrophic Mires*. Edinburgh: Scottish Natural Heritage.

MacKenzie NA, Worrell R (1995) *A Preliminary Assessment of the Ecology and Status of Ombrotrophic Wooded Bogs in Scotland*. Scottish Natural Heritage Report No. 40.

Macklin MG, Johnstone E and Lewin J (2005) Pervasive and long-term forcing of Holocene river instability and flooding in Great Britain by centennial-scale climate change. *The Holocene* 15: 937–943.

Mannerkoski H (1991) Relation between tree roots and soil aeration on drained peatlands. In: Jeglum JK, Overend RP (eds) *Peat and Peatlands – Diversification and Innovation*. Canadian Society for Peat and Peatlands, 109–114.

Mayewski PA, Rohling EE, Stager JC, Karlen W, Maasch KA, Meeker LD *et al.* (2004) Holocene climate variability. *Quaternary Research* 62: 243–255.

McHaffie H, Legg CJ, Worrell R and Amphlett A (2002) Scots pine growing on forested mires in Abernethy Forest, Strathspey, Scotland. *Botanical Journal of Scotland* 54: 209–219.

McNally A, Doyle GT (1984) A study of sub-fossil pine layers in a raised bog complex in the Irish midlands: 1. Palaeowood extent and dynamics. *Proceedings of the Royal Irish Academy B* 84: 57–70.

McVean DN (1963) Growth and mineral nutrition of Scots pine seedlings on some common peat types. *Journal of Ecology* 51: 657–670.

Mighall TM, Lageard JGA, Chambers FM, Field MH and Mahi P (2004) Mineral deficiency and the presence of *Pinus sylvestris* on mires during the mid to late Holocene: Palaeoecological data from Cadogan's Bog, Mizen Peninsula, Co. Cork, southwest Ireland. *The Holocene* 14: 95–109.

Moir AK (1996) Dendrochronological report on pine (*Pinus sylvestris* L.) stump samples: An initial investigation – Appendix 5.3. In: Binney HA, Holocene vegetation change and tree-line dynamics in the Scottish Highlands. Unpublished Ph.D. Thesis, London Guildhall University.

Pilcher JR (1990) Ecology of subfossil oak woods on peat. In: Doyle GJ (ed.) *Ecology and Conservation of Irish Peatlands*. Royal Irish Academy, 41–47.

Pilcher JR (1991) Radiocarbon dating for the Quaternary scientist. *Quaternary Proceedings* 1: 27–33.

Pilcher JR, Baillie MGL, Brown DM, McCormac FG, MacSweeney PB and McLawrence AS (1995) Dendrochronology of subfossil pine in the north of Ireland. *Journal of Ecology* 83: 665–671.

Schoning K, Charman DJ and Wastegård S (2005) Reconstructed water tables from two ombrotrophic mires in eastern central Sweden compared with instrumental meteorological data. *The Holocene* 15: 111–118.

Schouten MGC, Streefkerk JG and van der Molen PC (1992) Impact of climate change on bog ecosystems, with special reference to sub-oceanic raised bogs. *Wetland Ecology and Management* 2: 55–61.

Schweingruber FH (1996) *Tree Rings and Environment. Dendroecology*. Paul Haupt, Swiss Federal Institute for Forest, Snow and Landscape Research.

Schweingruber FH, Fritts HC, Bräker OU and Schar E (1979) Dendroclimatic studies on conifers from central Europe and Great Britain. *Boreas* 8: 427–452.

Stroud DA, Reed TM, Pienkowski MW and Lindsay RA (1987) *Birds, Bogs and Forestry*. Nature Conservancy Council.

Succow M, Joosten H (2001) *Landschaftsökologische Moorkunde*. Schweizerbart.

Tallis JH, Switsur VR (1983) Forest and moorland in the south Pennine uplands in the Mid-Flandrian period. I. Macrofossil evidence of the former forest cover. *Journal of Ecology* 71: 585–600.

Tipping R (2007) Storminess as an explanation for the decline of pine woodland ca. 7,400 years ago at Loch Tulla, western Scotland. *Vegetation History and Archaeobotany* 17: 345–350.

Tipping R, Davies A and Tisdall EW (2006) Long-term woodland dynamics in West Glen Affric, northern Scotland. *Forestry* 79: 351–359.

Tipping R, Ashmore P, Davies A, Haggart BA, Moir AK, Newton A *et al.* (2007) Peat, pine stumps and people: Interactions behind climate, vegetation change and human activity in wetland archaeology at Loch Farlary, northern Scotland. In: Barber J, Clark C, Cressey M, Crone A, Hale A, Henderson J *et al.* (eds) *Archaeology from the Wetlands: Recent Perspectives*. Society of Antiquaries of Scotland, WARP Occasional Paper 18, 157–164.

Tipping R, Ashmore P, Davies A, Haggart BA, Moir AK, Newton A *et al.* (2008) Prehistoric *Pinus* woodland dynamics in an upland landscape in northern Scotland: The role of climate change and human impact. *Vegetation History and Archaeobotany* 17: 251–267.

Turney CSM, Baillie M, Palmer JG and Brown DM (2006) Holocene climatic change and past Irish societal response. *Journal of Archaeological Science* 33: 34–38.

Väliranta M, Korhola A, Seppä H, Tuittila E-S, Sarmaja-Korjonen K, Laine J *et al.* (2007) High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: A quantities approach. *The Holocene* 17: 1093–1107.

White JEJ (1998) *Estimating the Age of Large and Veteran Trees in Britain*. Forestry Commission, Information Note, 250.

Wilkins DA (1984) The Flandrian woods of Lewis (Scotland). *Journal of Ecology* 72: 251–258.

Zetterberg P, Eronen M and Briffa KR (1994) Evidence on climatic variability and prehistoric activities between 165 BC and AD 1400 derived from subfossil Scots pine (*Pinus sylvestris* L.) found in a lake in Utsjoki, northernmost Finland. *Bulletin of the Geological Society of Finland* 66: 107–124.