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Reconstructing Holocene climate from tree rings: The potential for a long chronology from the Scottish Highlands

R. Wilson,[1] N.J. Loader,[2] M. Rydval,[1] H. Patton,[1] A. Frith,[1] C.M. Mills,[1] A. Crone,[3] C. Edwards,[4] L. Larsson[5] and B.E. Gunnarson[6,7]

Abstract

Despite promising research in the 1980s showing the potential of Scots pine (*Pinus sylvestris* L.) for the reconstruction of past summer temperatures in the Scottish Highlands, little dendroclimatic work has been attempted in this region since. This reflects, in part, the limited number of sparsely distributed remnant natural/semi-natural pine woodlands in the Scottish Highlands and the lack of old growth forest therein. On average, most of the pine trees dated in this region are around 225 years in age. Here, we present the first results of an ongoing interdisciplinary initiative to develop a long Scottish chronology through the acquisition of modern, historical and subfossil pine material from the native pinewoods, historic structures and lakes of the Scottish Highlands. Radiocarbon dating of 25 subfossil pine timbers recovered from lake sediments identified the presence of preserved material covering the last 8000 years with initial clusters focused on the last two millennia and early–mid Holocene. Although developing a well-replicated 8000 year pine chronology will take many years, this preliminary study indicates that a millennial length pine chronology from the northwest Cairngorm region is a feasible and realistic objective in the near future. The importance of such a record in this climatically important sector of northwest Europe cannot be underestimated.

Keywords

blue intensity, Holocene, palaeoclimate, Scotland, Scots pine, subfossil, tree-rings

Introduction

Climatologically, Scotland is distinct from mainland Europe because of its proximity to the North Atlantic. The influence of the Arctic Oscillation (AO) and its regional expression, the North Atlantic Oscillation (NAO), is especially strong in this region for both the winter and summer seasons (Cook et al., 2002; Dawson et al., 2004; Folland et al., 2009; Linderholm et al., 2008; Thompson and Wallace, 1998). Changes in the strength and persistence of these synoptic phenomena influence large-scale climatic variability across northwestern Europe (Trouet et al., 2009). Consequently, the development of long proxy records for this climatologically important region should be a priority for palaeoclimatologists.

Currently, in the UK, there are relatively few high resolution palaeoclimate proxy records covering the last millennium. Quantified >1000 year long reconstructions have been developed from speleothems (NW Scotland, Proctor et al., 2000, 2002) and water-table estimates using testate amoebae (multiple regions in the UK, Charman et al., 2006; Langdon et al., 2003), but these records are difficult to interpret because of conflicting influences of both temperature and precipitation while their temporal interpretation is further exacerbated as a result of error uncertainties in age–depth modelling. Tree-ring records have been utilised from several locations around the Northern Hemisphere to produce annually resolved millennial or longer local/regional reconstructions of temperature (Büntgen et al., 2005, 2006; Esper et al., 2003; Grudd, 2008; Linderholm and Gunnarson, 2005; Luckman and Wilson, 2005; Wilson et al., 2007). However, in the UK, dendroclimatology has had limited success because of either weak or mixed climatic signals, as noted in long (> 1000 years) English oak records (Hughes et al., 1978; Kelly et al., 2002), or the relative shortness (~200–300 years) of temperature-sensitive living Scots pine (*Pinus sylvestris* L.) records from the Scottish Highlands (Fish et al., 2010; Hughes et al., 1984; Mills, 2008).

Figure 1 shows a spatial correlation map between gridded terrestrial July–August (JA) temperatures (CRU3) for the 5°×5° terrestrial grid over Scotland and HADCRU3 temperatures (Brohan et al., 2006) across the European and North Atlantic region. Also shown are the locations of existing published > 1000 year long tree-ring based summer temperature reconstructions in Europe (Büntgen et al., 2005, 2006; Grudd, 2008; Linderholm and Gunnarson, 2005). Acquiring a similar tree-ring based temperature reconstruction for Scotland would not only fill an important spatial gap within the European region (see also Büntgen et al., 2010), but could also provide important information on the past behaviour of the AO and NAO (Cook et al., 2002; Folland et al., 2009; Linderholm et al., 2008; Thompson and Wallace, 1998).

[1]University of St Andrews, UK
[2]Swansea University, UK
[3]AOC Archaeology, UK
[4]Forest Research, UK
[5]Cybis Elektronik & Data AB, Sweden
[6]Swedish University of Agricultural Sciences, Sweden
[7]Stockholm University, Sweden

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Corresponding author:
R. Wilson, School of Geography & Geosciences, University of St Andrews, St Andrews KY16 9AL, UK.
Email: rjsw@st-andrews.ac.uk

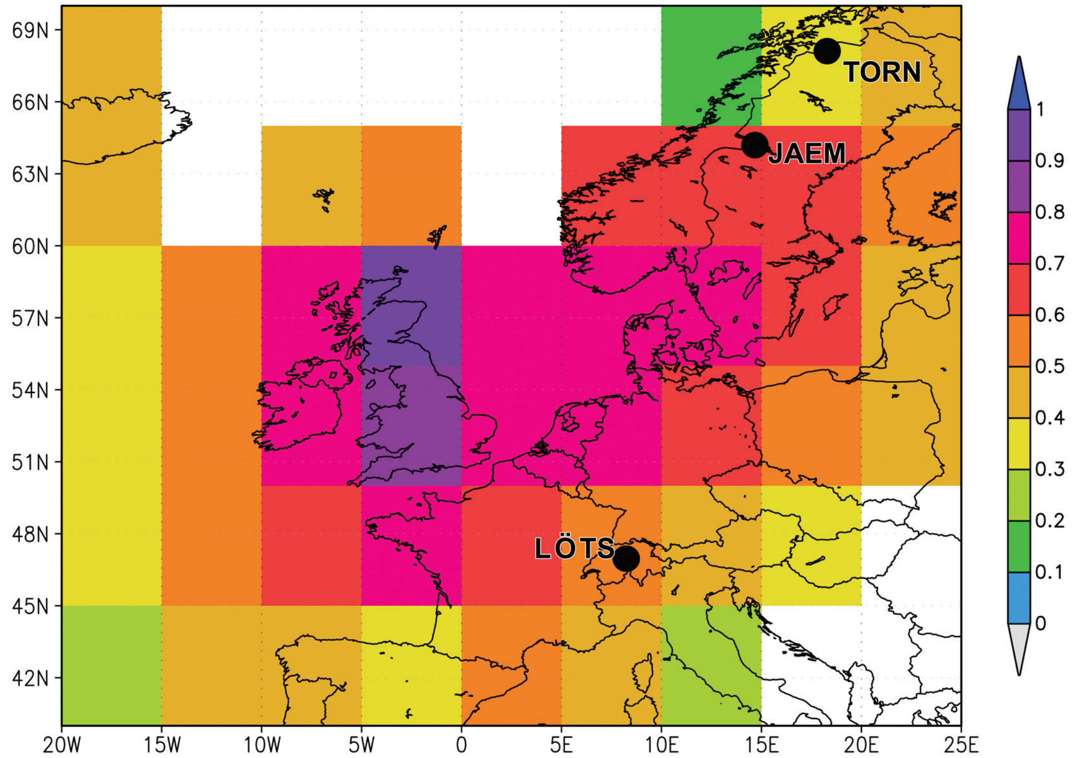

Figure 1. Spatial correlations (1850–2009 for July–August) between the relevant terrestrial grid over Scotland (55–60°N 5–0°W) with gridded (5°×5°) HADCRU3 temperatures over Europe (Brohan et al., 2006). The dots show the locations of published millennial-long tree-ring based reconstructions in Europe: TORN, Torneträsk (Grudd, 2008); JÄEM, Jämtland (Gunnarson and Linderholm, 2002; Linderholm and Gunnarson, 2005); LÖTS, Lötschental (Büntgen et al., 2005, 2006)

Hughes et al. (1984) showed that a strongly calibrated reconstruction of Edinburgh summer (July–August) mean temperatures ($r^2 = 0.58$) could be derived using ring-width (RW) and maximum latewood density (MXD) measurements obtained from several pine sites throughout the Scottish Highlands. However, despite the robust calibration/verification results, the Hughes et al. (1984) reconstruction only went back to AD 1721 and they concluded that:

> Further sampling of ancient living trees should allow the extension of the Edinburgh record back into the seventeenth century, the most severe phase of the Little Ice Age, and result in a valuable reconstruction. A proxy record for more distant times may be obtained using the large quantities of sub-fossil pine found in the British uplands.

Further sampling, for dendroclimatological purposes, has not been made since and this is the main rationale for the research detailed here. This paper is divided into two sections. First, the current status of the living Scots pine network is described as it has been substantially expanded since Hughes et al. (1984). The second section reports on preliminary investigations to recover subfossil material from Scottish lakes and the potential for using this material to extend the living chronologies back in time.

An updated and expanding living Pine network

Over recent years, a systematic re-sampling of the longest Hughes et al. (1984) tree-ring sites has been made as well as the sampling of many new locations (Figure 2). Of the original ~1 500 000 ha area covered by Scots pine woodland during the mid Holocene,

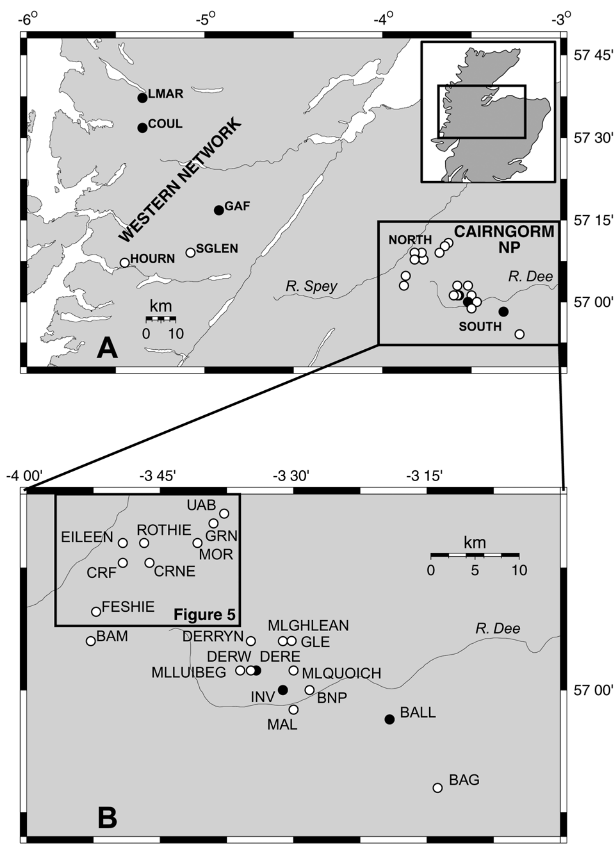

Figure 2. Location map of sampled pine woodlands around Scotland. (A) All sites in Scotland. (B) The Cairngorm National Park (NP) region. In-filled circles denote sites originally sampled for Hughes et al. (1984) and updated as part of this study

Table 1. Pine site information. The updated Hughes et al. (1984) sites are shown by the International Tree-Ring Databank (ITRDB) codes. From the original Hughes et al. (1984) study, the sites Drimmie (archived as Dimmie, Brit021), Loch Morar (Brit049), Plockton (Brit048) and Shieldaig (Brit016) have not yet been updated and so are not included in the current summary

Region	Site Name	Site Code	ITRDB code	Latitude	Longitude	Elevation	First Year	Last Year	No. of series	Period cover by >=10 series	Parameters
Western Scotland	Coulin	COUL	Brit026	57.32	5.21	250	1636	2009	67	1702–2009	RW/MXD/BI
	Loch Maree	LMAR	Brit018	57.37	5.21	100	1621	2009	70	1748–2009	RW/MXD/BI
	Glen Affric	GAF	Brit024	57.17	4.55	250–350	1704	2009	179	1714–2009	RW/MXD/BI
	Southern Glens	SGLEN		57.09	5.05	240–370	1458	2007	57	1559–2003	RW/18O/13C/2H
	Loch Hourn	HOURN		57.07	5.27	90–240	1802	2007	10	1859–2007	RW/18O/13C
North Cairngorms	Loch a' Gharbh choire	UAB		57.11	3.38	410–420	1735	2009	26	1783–2009	RW
	Green Loch	GRN		57.10	3.39	370–480	1655	2009	58	1740–2009	RW
	Morlich	MOR		57.09	3.41	410–450	1740	2006	17	1788–2006	RW
	Carn Eilrig	CRNE		57.08	3.46	480–540	1735	2008	23	1824–2008	RW
	Rothiemurchus	ROTHIE		57.09	3.47	290–330	1841	2006	17	1853–2006	RW
	Loch an Eilein	EILEEN		57.09	3.49	260	1755	2008	53	1850–2008	RW/BI
	Creag Fhiaclach	CRF		57.08	3.49	500–550	1736	2008	18	1845–2008	RW/BI
	Feshie	FESHIE		57.05	3.52	480–540	1811	2006	24	1849–2006	RW
	Badan Mosach	BAM		57.03	3.53	370–420	1763	2008	25	1845–2008	RW/BI
South Cairngorms	Derry East	DERE	Brit020	57.01	3.34	480–530	1629	2008	54	1741–2008	RW/MXD
	Derry North	DERRYN		57.03	3.35	530–600	1477	2008	32	1640–2008	RW
	Derry West	DERW		57.01	3.35	450–520	1723	2008	18	1773–2009	RW
	Luibeg	MLLUIBEG		57.01	3.36	460–540	1657	2008	31	1711–2008	RW
	GhleannWest	MLGHLEAN		57.03	3.31	480–550	1744	2008	24	1764–2008	RW
	GhleannEast	GLE		57.02	3.28	490–540	1697	2008	31	1760–2008	RW
	Quoich	MLQUOICH		57.01	3.30	430–500	1680	2008	24	1733–2008	RW
	Inverey	INV	Brit015	57.00	3.31	500–550	1706	2008	41	1731–2008	RW/MXD/BI
	Upper Punch Bowl	BNP		57.00	3.28	450–550	1681	2008	22	1839–2008	RW
	Mar Lodge	MAL		56.59	3.30	350	1831	2008	26	1837–2008	RW/BI
	Ballochbuie	BALL	Brit017	56.58	3.19	300–500	1589	2003	48	1688–2003	RW/MXD/ 18O/2H/13C
	Bachnagairn	BAG		56.54	3.14	500–560	1833	2008	20	1847–2008	RW

only about 1% now remains, and of these remnant patches, most are in a semi-natural state (Smout et al., 2005). This small amount of remaining woodland, however, provides an opportunity to develop tree-ring chronologies from all locations in Scotland where semi-natural pine woodlands still exist. Such a densely sampled network will not only allow a detailed assessment of the different environmental controls affecting tree growth (i.e. identification of the different effects of local/regional climate, ecology and management), but will also potentially allow the provenancing of dendro-dated construction timbers from local historical structures (Mills, 2008).

Table 1 provides summary information of the current Scots pine network. Six of the longest Hughes et al. (1984) sites (COUL, LMAR, GAF, DERE, INV, BALL) have been updated to the present while a further 20 new locations have been sampled. Much of the new pine sampling has focused on the Cairngorms National Park (Figure 2B) as it is here where substantial subfossil material has been found (see below) although ongoing sampling is now focusing on expanding the western network (Figure 2A). Many of the pine woodlands represent woodland ecosystems recovering from multiple thinning and clear cutting events since the sixteenth century (Fish et al., 2010; Smout et al., 2005). Although on average most mature pine trees are around ~225 years in age (Fish et al., 2010), individuals > 400 years have been found in the Southern Glens (Mills, 2005; Woodley, 2010), North Derry (Mills, 2009) and Ballochbuie woodlands (Loader and Switsur, 1996; Mills, 2006).

Regional climate response and palaeoclimate potential

This paper focuses primarily on the potential for extending the living pine chronologies using subfossil material. The following section, therefore, only briefly presents initial investigations into the regional response of the living tree-ring data to changes in mean temperature and evaluates the potential of these data for reconstructing past temperatures. The analysis is undertaken using only the Cairngorm tree-ring data as it is across this region where modern sampling is currently the most complete and where significant subfossil material has been recovered and dated. Results are presented for two established palaeoclimate proxies (ringwidth (RW) and maximum latewood density (MXD)) while preliminary results are presented for blue intensity (BI). BI is a relatively new parameter in dendroclimatology and has been shown to express a similar climate signal to MXD (Babst et al., 2009; Campbell et al., 2007; McCarroll et al., 2002). For those sites where BI was measured, 10–15 cores were mounted and sanded following standard dendrochronological methods. The mounted cores where then soaked in pure acetone for 72 h to extract resins. Ideally, resin extraction should be conducted prior to mounting the core for measurement. However, for this preliminary investigation, we purposely adopted this approach to assess whether resin could be adequately extracted and a robust BI signal developed from pre-mounted cores as many mounted core samples, initially collected for conventional

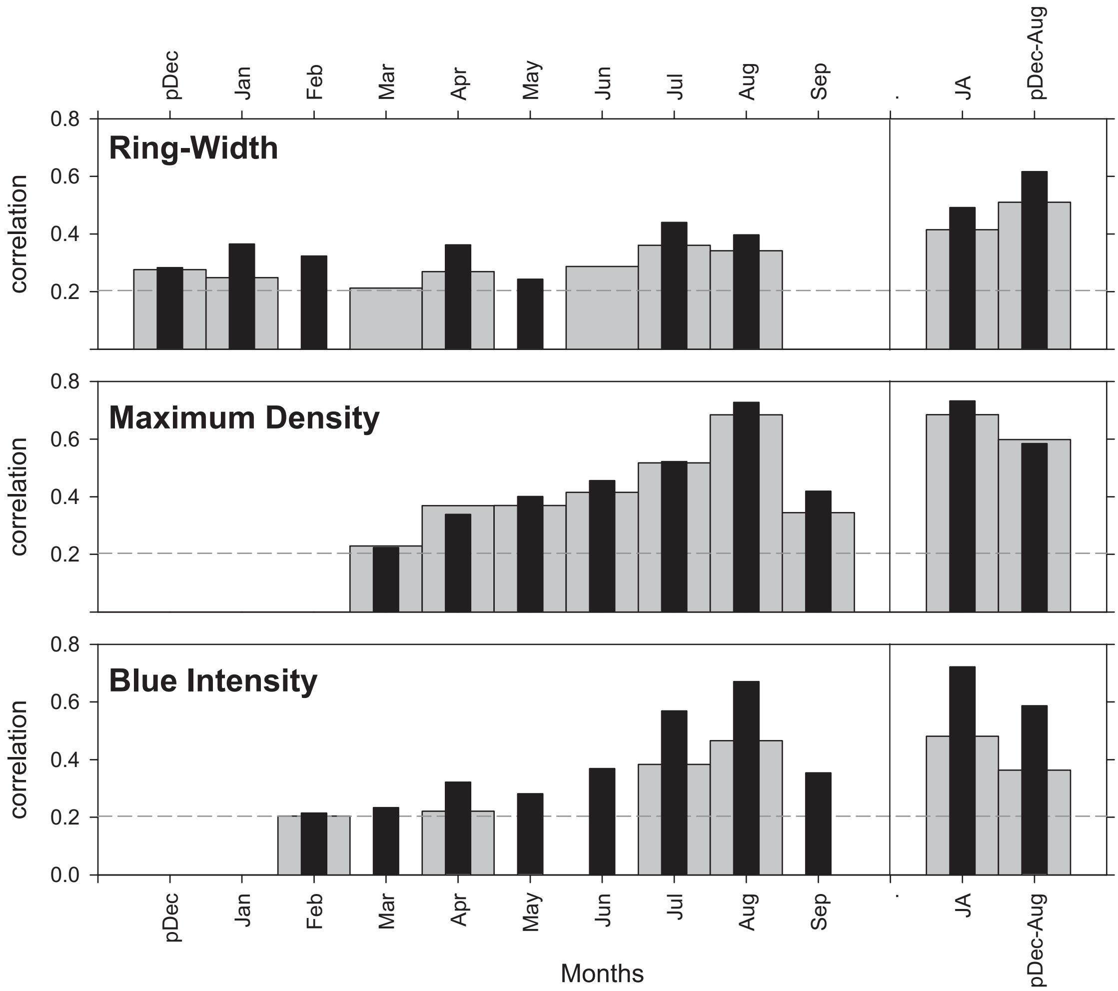

Figure 3. Correlation response function analyses (1851–1978) between the RW, MXD and BI composites and monthly temperature variables. Only significant correlations (99% C.L.) are shown. The wide grey vertical bars represent correlations using non-transformed time-series while the thin black bars represent results from using 1st differenced transforms of the data. The RW data were detrended using traditional negative exponential functions or regression functions of negative or zero slope. Before detrending, the BI data were inverted as they are inversely correlated with MXD data. The MXD and BI data were detrended using regression functions of negative or zero slope

dendrochronology/dendroclimatology, already exist for sites across Scotland (Table 1). As BI records a measure of surface reflectance, it may therefore be possible to access this significant existing archive, without remounting of samples, to provide additional palaeoclimate information.

Fish et al. (2010), using a reduced network than is currently available (Table 1 and Figure 2), showed that there was a generally consistent moderate response of pine RW chronologies to temperature across Scotland. The dominant response of pine RW data to climate is with both winter and summer mean temperatures, although unsurprisingly, the weighting of this response is stronger for the growing season and the response to winter temperatures appears not to be time-stable and weakens through the twentieth century (Fish et al., 2010; Paton, 2010). Figure 3 confirms this overall response of RW to temperatures using a composite record derived from all the sites in the Cairngorms (Table 1). Significant correlations (99% confidence level) are found with winter, spring and summer temperatures which marginally improve when the data are 1st differenced. Strongest correlations are found with the extended previous December–August season.

As expected, the response of the MXD data (composite of DERE, INV and BAL; Hughes et al., 1984) to monthly temperatures is stronger than with the RW data with a significant relationship being noted from March through to September. The correlation with July–August (JA) temperatures – the season reconstructed by Hughes et al. (1984) – is 0.68. There is little difference in response between the non-transformed and 1st-differenced versions of the data.

BI data were generated for five sites in the Cairngorms (Frith, 2009) – EILEEN, CRF, BAM, INV and MAL (Table 1 and Figure 2B) – and these data were averaged to derive a composite series for this current analysis. The MXD and BI composite records are strongly correlated ($r = 0.70$, and 0.83 after 1st differencing, Table 2) highlighting a strong covariance between the data. The response of the BI data to temperature (Figure 3) is also similar to that of the MXD data, but for the non 1st-differenced transformed versions, is generally weaker with the correlation to JA temperatures at 0.48. However, after the BI and climate data are transformed to 1st differences, the correlation response function results increase significantly for the JA season to 0.72.

These results imply that the climate signal in these BI data is stronger at inter-annual timescales than at decadal or longer timescales. These frequency-dependent results for the BI data suggest that the method used for resin extraction from mounted cores was likely not fully successful in extracting all the resins and that this has resulted in lower frequency biases (due to a relatively darker

Table 2. Correlation matrix (1743–1978) between the RW, MXD and BI composite time-series. Values in bold are for 1st differenced transforms of the chronologies. Note: the BI data have been inverted to yield positive correlations

	RW	MXD	BI
RW		0.40	0.33
MXD	**0.36**		0.70
BI	**0.40**	**0.83**	

heartwood compared to the sapwood) in the resultant BI raw data. However, the 1st difference correlation response functions (Figure 3) indicate that the inter-annual signal is very strong. Continuing BI measurement and experimentation is now focusing on extracting the resin before the mounting of the cores to reduce lower frequency biases in the resultant data. Overall, however, Figure 3 indicates that RW, MXD and BI measurements from Scots pine portray a significant temperature signal and extension of these living records would provide an important proxy of past temperatures.

We should note that in addition to physical growth proxies, additional environmental information may be obtained from dendrochemical analyses (Fairchild et al., 2009; McCarroll and Loader, 2004). Stable carbon, oxygen and hydrogen isotope analyses have also been carried out on Scots pine from BALL, SGLEN and HOURN (Loader and Switsur, 1996; Loader et al., 2003; Woodley, 2010) where coherent trends were noted between stable isotope ratios and growing season conditions indicating that environmental information is preserved within the dendrochemistry of trees growing in this region.

Subfossil pine material and the development of a long Scottish pine chronology

Despite the clear potential of using Scots pine (*Pinus sylvestris* L.) for dendroclimatic reconstruction (Hughes et al., 1984; Figure 3), a significant challenge in Scotland is the extension of the living pine chronologies back in time, as has been conducted using oak (Crone and Mills, 2002). Radiocarbon dating of subfossil pine material preserved in peat bogs has, however, been used to provide information on the spatial and temporal distribution of pine in Scotland over the last ~ 8000 years (Bridge et al., 1990; Dubois and Ferguson, 1985; Gear and Huntley, 1991; Moir et al., 2010; Pears, 1988; Tipping et al., 2008; Ward et al., 1987). However, dendrochronological techniques could rarely be applied to the samples in these studies because of decay and the fact that many of the samples were taken from the root stock where the rings are distorted and the trees were relatively short-lived. Similarly, Scots pine trees growing on bogs have not yet been shown to portray a valid climate signal compared with trees growing on drier mineral soil sites (Linderholm et al., 2002).

The key, therefore, to extending the Scottish living pine chronologies for dendroclimatic purposes lies NOT in using incomplete, distorted pine samples from peat bogs, but finding sources of complete stems where clearly defined, long tree-ring sequences can be found. In Fennoscandia, very long (> 5000 years) pine chronologies have been developed using subfossil wood preserved in lake sediments (Eronen et al., 2002; Grudd, 2008; Grudd et al., 2002; Gunnarson, 2008; Linderholm and Gunnarson, 2005). To date, no equivalent attempt has been made in Scotland to find such lake material. However, palynological and macrofossil analysis has shown that Scots pine has grown continuously for the last ~ 8000 years in the eastern areas of Glen Affric and in the northwestern (NW) Cairngorm regions of the Scottish Highlands (Figure 2; Bennett, 1995; Froyd and Bennett, 2006; O'Sullivan, 1974, 1976; Shaw and Tipping, 2006). These regions are therefore critical areas for locating subfossil pine remains to derive a continuous pine chronology for most of the Holocene period.

In spring 2008, a survey was made of the NW Cairngorm region (Figures 2 and 4) to identify lakes with subfossil pine material preserved in their sediments. Subfossil pine stems were found in many small lakes – even above the present treeline. However, abundant material was noted in two lakes (Loch an Eilein and Loch Gamnha) in the Rothiemurchus Estate and the Green Loch (An Lochan Uaine) in Glenmore Forest Park (Figure 4). 25 preliminary samples were taken from Loch an Eilein and Loch Gamnha for radiocarbon dating to ascertain the approximate time frame represented by the material recovered. Figure 5 compares the results of the ^{14}C dating of this lake material against previously published dates of pine material extracted from peat bogs around Scotland. The time period covered by these initial 25 samples is from 200 to 8000 yr BP. The dating of the samples, however, is clustered, with seven samples grouping to ~7800 yr BP, a few samples between 2000 and 3000 yr BP and the rest covering the last 1200 years. Intriguingly, no dated samples were found around ~4500–5000 yr BP – the period of the so called, and much debated, 'pine decline' – suggesting that there was no regional-scale dieback of the pines trees at this time around these two lakes.

Scots pine (*Pinus sylvestris* L.) first colonised NW Scotland around 8000 yr BP (Birks, 1972) with clear evidence of pine woodland occurring in the Speyside region (Figure 4) to the NW of the Cairngorms at this time (O'Sullivan, 1974, 1976). As the climate warmed after 7500 yr BP, pine forests expanded rapidly, attaining maximal coverage ~6000 yr BP (Bennett, 1984). However, ~4000 yr BP, a collapse in pine woodland has been shown from both dated pine stumps preserved in blanket peat (Birks, 1975; Bridge et al., 1990; Gear and Huntley, 1991) and pollen records (Birks, 1989; Tipping et al., 2006). Whilst these studies showed relatively good agreement over large areas, recent research, as well as the results shown here, question the theory of a Scotland-wide 'pine decline' (Tipping, 2008) with some studies able to demonstrate that some Scottish pine communities were locally present and have remained relatively stable since 8300 yr BP (Froyd and Bennett, 2006; Tipping et al., 2006).

The challenge of developing a long Scottish pine chronology

In 2009, ~40 pine macrofossil samples were taken from Loch an Eilein (Figure 4) to provide further 'proof of concept' evidence for the development of a long Scottish pine chronology. Using these new samples with the original samples from 2008, it has become clear that huge challenges need to be overcome before a continuous well-replicated 8000-year pine chronology can be developed for the Scottish Highlands.

So long as there is a common signal in tree-growth across a region, the success of crossdating tree-ring samples is mainly related to the number of rings in the overlap between samples. The probability of acquiring a correct crossdate between samples increases as the number of years in the overlap increases. However,

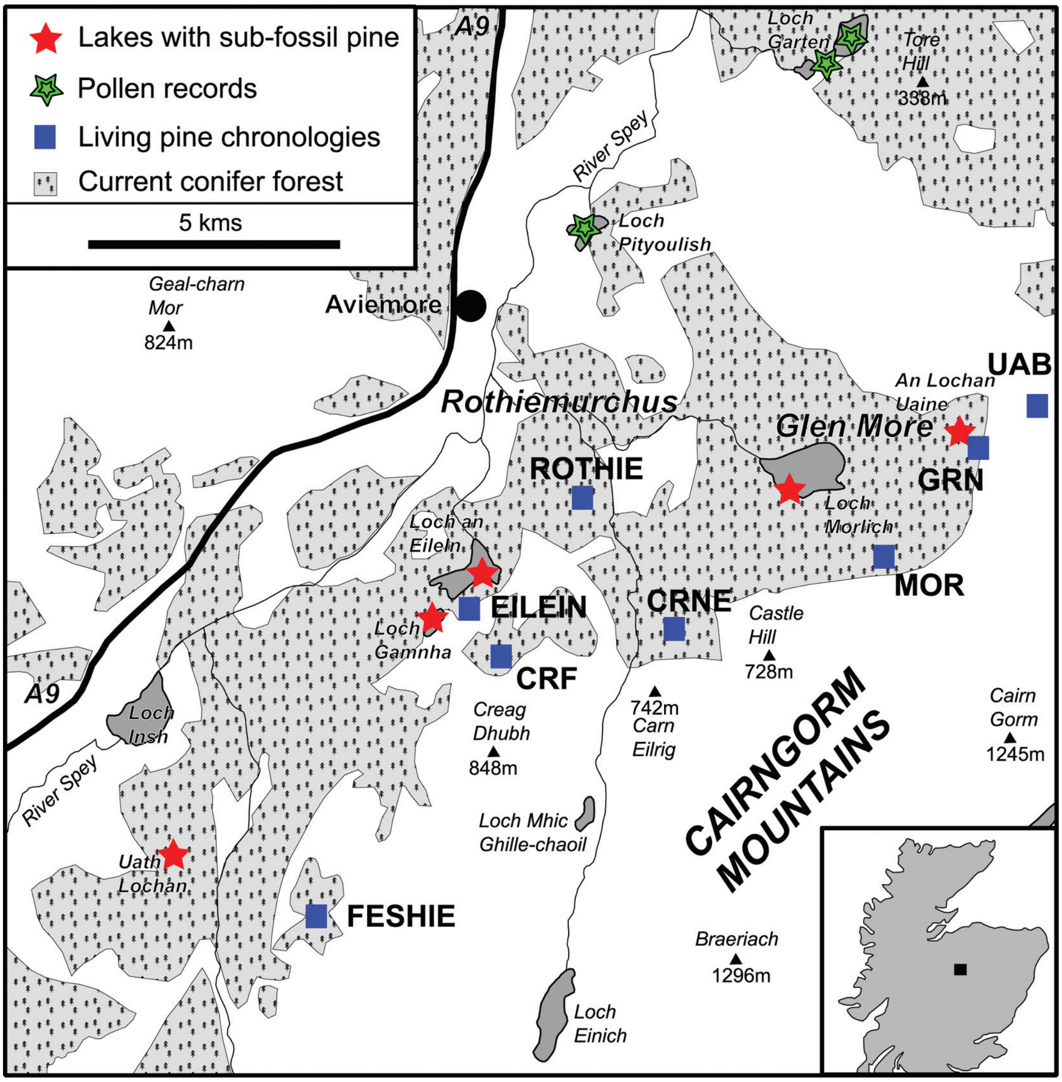

Figure 4. Location map of the current main study area in the northwest Cairngorms

pine RW series are strongly autocorrelated (mean 1st order AC for detrended subfossil material = 0.65), which means that much of their variability is dominated by trend that could lead to spurious crossmatches between samples. Of the ~40 samples taken in 2009, the average number of measured rings is 88 years, with a sample age range from 20 to 239 years. This range in ages not only represents the complex stand dynamics (young versus old) of the pine woodland through time (rarely seen in current managed woodlands (Fish et al., 2010)), but also the fact that the number of rings measured for some of the very old samples likely underestimate the age of the trees at death as the sapwood has been lost through decay.

Therefore, with an average number of rings of the subfossil samples being only ~90 years, the chance of spurious crossmatches between samples is potentially very high. To further exacerbate the situation, there is also a small chance of missing rings which, unlike samples from living trees of known age, are difficult to identify in less well-replicated subfossil material of unknown date. To overcome these difficulties and to minimise incorrect dating, we propose an idealised multistep approach to crossdating:

(1) Using computer-based crossdating methods (e.g. using software such as COFECHA (Grissino-Mayer, 2001), CROS (Baillie and Pilcher, 1973), the 'Dendro' suite (Tyers, 1999), or CDendro (http://www.cybis.se/forfun/dendro/index.htm)), empirical crossmatches are first sought between RW series using standard methods. We propose also, however, that a second set of comparisons be made after the tree-ring data are transformed to 1st differences. This latter transformation is an important step as it ensures that the transformed time-series are not autocorrelated and dating is purely made on the inter-annual signal. However, we should emphasise that whatever method is used for crossdating, the probability of a successful crossmatch increases as the number of years in the overlap increases.

(2) Any potential crossmatch of RW data identified using COFECHA should be qualitatively viewed by graphing the detrended time-series. Although qualitative, this visual comparison is an important step to ensure that the series do track each other well over their period of overlap.

(3) Figure 3 clearly shows the potential of the BI parameter as a climate proxy, at least at inter-annual timescales, while Table 1 shows that the BI data are only weakly correlated with the RW data (r = 0.33; 0.40 after 1st differencing). The BI parameter may therefore act as an independent data source with which to undertake crossdating. If consistent crossmatches are identified for samples using both RW and

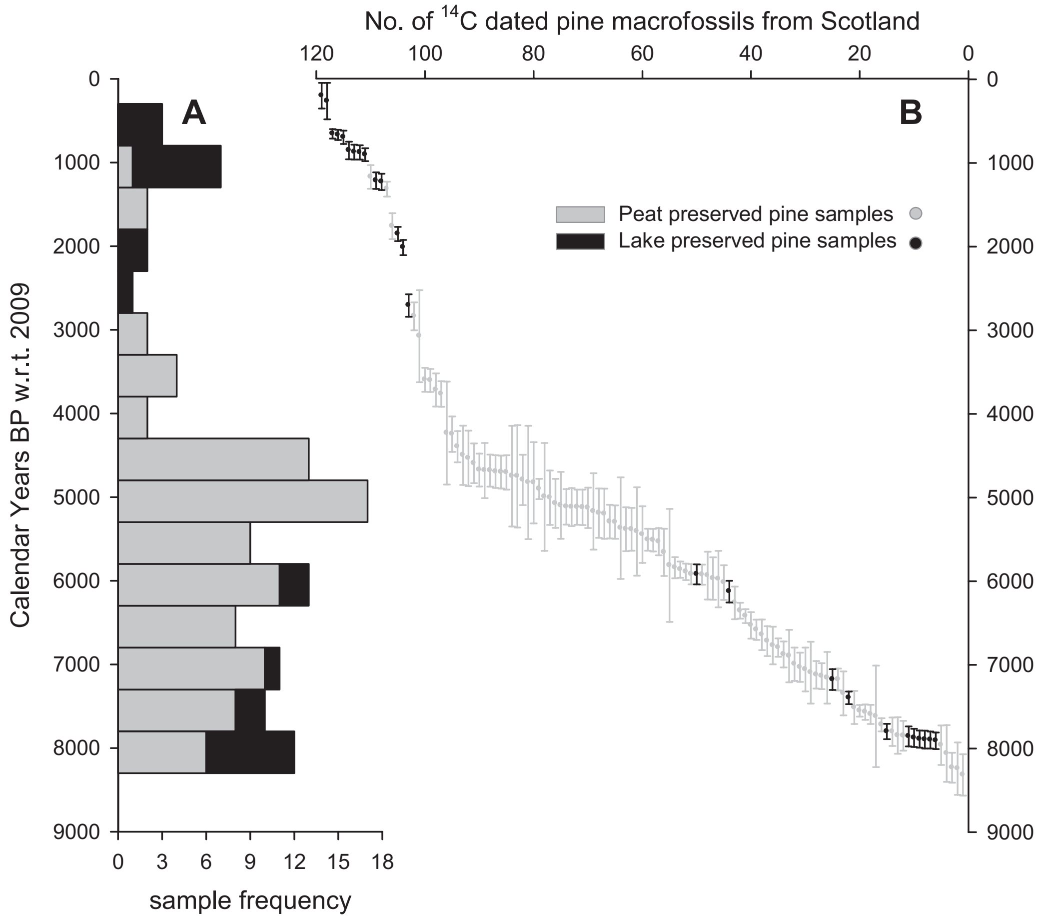

Figure 5. ^{14}C age comparison of pine macrofossils preserved within peat (grey bars) (data taken from Bridge et al., 1990 (and references therein) and Gear and Huntley (1991) and lakes (black bars) within the Scottish highlands, showing (A) the number of samples for 500 yr periods and (B) the ages (1 sigma error) of individual samples

BI data, this would provide strong evidence that a correct crossdate has been found.

(4) Finally, Figure 5 highlights the importance of ^{14}C dating in constraining samples to the correct period in the Holocene. Although it is unrealistic to assume that there will be enough funds to carbon date all subfossil samples, multiple ^{14}C dating will be vital to ensure that at least some strategically chosen (long-lived) samples within crossdated clusters are temporally constrained, therefore validating the dating within the clusters. Such dating will ensure important 'tie' points within the chronology as it develops.

Ultimately, the success for any chronology development comes down simply to sample replication. For the Cairngorms therefore, if the mean number of rings per subfossil sample is only ~90 years, many thousands of samples will ultimately be required before a continuous ~8000 year long chronology can be developed. How quickly this ultimate goal can be achieved will depend on how many macrofossil pine samples can be extracted from the lakes.

There are several reasons why pine stems may enter the lake environment and become preserved in the sediments. First, there is the random effect of shoreline trees dying naturally and falling into the lake. This is likely to be a low-probability event and for any one lake (size dependent of course) we hypothesise that very few trees will fall 'naturally' into a lake during any one century. If an optimal replication of ~20 trees is desired to pass signal strength statistics (Wigley et al., 1984), then many lakes would have to be sampled in a region to acquire such sample depth. However, there will be a much higher probability of tree death clustering during periods of either increased human land use (i.e. associated with forest clearance, as logs were initially floated upon lakes and transported down rivers) or periods of extreme climate (i.e. related to lake level changes, or extreme wind storm events, etc).

The initial radiocarbon dating results (Figure 5) clearly show the presence of well preserved pine macrofossil material covering different periods over the last ~8000 years which highlights the possibility of developing a long pine chronology for this region. Using the subfossil samples taken in 2008 and 2009 and the standard and 1st differenced dating approach for ring-widths described above (note: the BI parameter has yet to be measured on the subfossil samples), preliminary dating results using both between-sample crossdating and radiocarbon dating are presented (Table 3). Despite the relatively low number of samples collected so far, these initial results are encouraging and already suggest that the development of a chronology covering the last millennium is a likely prospect as further samples are taken. The gap between the AD 1335–1483 ^{14}C dated cluster and the period covered by the Loch an Eilein living trees (AD 1755–2008) coincides with the period of greatest woodland management (clear-cutting and thinning) in the region (Smout et al., 2005). Much of this gap, however, can already be covered by other long chronologies from the Cairngorm region (Table 1).

Table 3. Preliminary clustered dating results with sample replication

Calendar date	No. of measured series	No. of dated trees	No. of years in cluster	No. of ^{14}C dates in cluster
1335–1483	12	6	149	3
1129–1336	8	4	208	2
1086–1189	3	2	104	2
723–905	3	3	183	2
−5956 to −5808	12	7	149	6
no date	7	3	239	0
1755–2008	53	53	254	0

Conclusion

This paper presents the initial results of the Scottish Pine Project; a multidisciplinary research team of dendrochronologists led by St Andrews University. Significant progress has been made sampling existing living pinewood remnants across Scotland by increasing spatial coverage and updating existing tree-ring chronologies. This has also resulted in the discovery of several long-lived trees in excess of 400 years which provide an important link for the development of long chronologies and archaeological tree-ring dating. Improved chronology coverage and replication across Scotland will improve our ability to dendrochronologically date and provenance locally sourced building timbers thereby providing insight into the historical and social development of modern Scotland. Preliminary climate analysis of the ringwidth, density and blue intensity data support the findings of Hughes et al. (1984) and demonstrate how extended, well replicated tree-ring records will provide a robust high resolution temperature reconstruction for the region.

Of particular significance is the discovery, recovery and dating of subfossil material preserved in lake sediments, providing a means by which chronologies developed from living trees may be extended back in time. Extending the living Scottish pine chronologies using subfossil material will be a huge challenge because of their generally short sample lengths. However, the concurrent use of both RW and BI parameters, as well as radiocarbon dating of select samples, will increase the chance of correctly crossdating tree-ring samples. Despite the early stage of this research, preliminary results (Table 3) using both radiocarbon dating and RW-based crossdating has identified clusters of samples that indicate that a millennial-length pine chronology from the NW Cairngorm region is a feasible and realistic objective in the near future. Such a record will provide a powerful tool with which to assess natural climatic variability and place recent observed changes/extreme events within a longer-term perspective. Importantly, by updating and developing new absolutely dated annually resolved climate reconstructions for this climatologically important region, the Scottish Pine Project will fill a gap (Büntgen et al., 2010) in the large-scale hemispheric mosaic of high resolution palaeoclimate proxy archives.

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