The dendroclimatology of Modern and Neolithic Scots pine (*Pinus sylvestris* L.) in the peatlands of northern Scotland

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Abstract

For the first time in northern Scotland, Modern tree-ring chronologies for Scots pine growing on peat are compared against those growing on mineral substrates. Mean tree-ring growth of pine on active bogs/mires is found to be limited to 0.5 to 1 mm yr^{-1}, compared to $\geq$1.5 mm yr^{-1} on adjacent mineral sites. Almost instant change of radial growth rates in response to changes in water levels highlights the potential use of pine in reconstructions of lake levels and water tables in bog and mire. Dendroclimatological analysis identifies January and February temperatures to often be more important than summer temperature. Positive correlation of ring-width and North Atlantic Oscillation (NAO) indices also occur in January and February. Lower winter temperatures, due to increased altitude and distance from the moderating effects of the ocean, may be important in limiting tree growth near its northern margin. Moving correlation functions identify a widespread reduction in the response of pine growing on both substrates from the 1920s.

Nine subfossil pine site chronologies located beyond the species current northern limit are cross-matched to form a chronology called WRATH-9. This chronology is tentatively crossdated against Irish pine chronologies to provide the first picture of Neolithic Scots pines 200 year expansion from *c*. 3200 BC and subsequent 250 year retreat across northern Scotland at annual resolution.

The mean orientation of maximum radial growth at eleven modern pine sites is found to coincide well with the W/SW prevailing wind, suggesting Scots pine may provide a good proxy indicator of wind. Six coeval Neolithic sites indicate a broadly consistent northerly prevailing wind. This provides tentative evidence for a change of prevailing wind that may be related to a southward incursion of the polar front in the eastern N. Atlantic. The potential of this exciting subfield of dendroclimatological analysis is called dendroaeology and is highlighted for further research.

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1 INTRODUCTION

This thesis uses dendrochronology to examine both Modern pine and palaeo-woodland in Scotland, to help understand the timing and reasons for a mid-Holocene migration north onto the surface of peat and then subsequent retreat and preservation. Increased awareness of the current and past socio-economic impacts of climate change (Turney *et al.* 2006), highlight the importance of this type of research.

On land, attempts to clarify the nature of climatic change during the Holocene, which started about 9500 ^{14}C cal. yr BC, (^{14}C cal. yr BC is a calibration applied to radiocarbon assays to make them conformable with calendar years before present, BC is an abbreviation for years “before Christ”), have long employed palynological methods. Vegetation in bogs is considered particularly sensitive to climate because they receive their water and nutrient supply from atmospheric precipitation. However, while it has long been assumed that records of bog surface wetness reflect changes in precipitation and temperature, understanding and quantification of the relationships remains unclear (Charman 2007).

Bogs in oceanic areas like the western British Isles are very sensitive to past changes in effective humidity, and so are more reliable archives of past climatic change than the *Sphagnum fuscum* dominated raised bogs in the more continental areas of north eastern and northern Europe (Barber *et al.* 2004). This is probably largely due to the maritime climate being dominated by prevailing westerly winds which are effectively free from the influences of major ice masses and continents and so may be sensitive to fluctuations in the strength of thermohaline circulation in the North Atlantic (Turney *et al.* 2005). Within the British Isles, Lowe & NASP members (1995) identify the Scottish uplands as especially important to research due to their sensitivity to climatic changes: changes that do not appear to be recorded in the more permanently wet lowland bogs of Ireland. Palaeohydrological and palaeoecological research on Scottish peat and lake sediments have been used to increase our understanding of the mid-Holocene climatic deterioration and to try to establish transitions to wetter climatic conditions (Bennett 1984, Bennett 1995, Birks 1996, Anderson *et al.* 1998). Advances in replication by correlating different proxies from different sites have been made (O'Connell *et al.* 2001, Barber *et al.* 2004, Langdon and Barber 2005). Advances in resolution by using time parallel markers, such as tephra isochrones, have also been developed and used in Scotland, (Dugmore 1989, Langdon and Barber 2001, Dugmore *et al.* 1995b, Langdon and Barber 2004, Barber *et al.* 2008), but there has been a failure to overcome the inherent problem of reliance on radiocarbon dating to provide chronological control. Hence, few refinements have been made in the timing of Holocene climatic transitions, particularly whether they were gradual or abrupt.

The peatlands of Northern Scotland are one of the largest and most intact areas of blanket bog (a globally rare ecosystem type) in the world (Stroud *et al.* 1987). In more continental parts of Europe it is the norm for bogs to be associated with trees (Moore 1984). However, the majority of relatively undisturbed bogs in the UK are currently treeless (Ellenberg 1988). Whether this is a natural state has only recently begun to be examined (Wells 2002), but Scots pine (*Pinus sylvestris* L.) has increasingly been recognized as a widespread component of the present day mire communities in Scotland. A regionally extensive horizon of subfossil pine, preserved in the peatlands of northern Scotland, shows that it flourished on this substrate between about 3500-2500 ^{14}C cal. yr BC (Huntley *et al.* 1997). This subfossil pine occurs well beyond the current ecological northern limit of Scots pine, located at about latitude 58° north (McVean and Ratcliffe 1962), and so provides strong evidence of environmental change.

The precise nature of episodes of pine decline and climate change in Scotland are not well defined (Tipping *et al.* 2006, Tipping *et al.* 2007b). They are most commonly assumed to have been in part a response to increased moisture (Dubois and Ferguson 1985, Bridge *et al.* 1990, Gear and Huntley 1991) but this has rarely been tested through independent measures of climate change (Tipping *et al.* 2007b). Godwin (1956) first suggested that: *"Scots pine may have grown on the surface of bogs ever since their formation, becoming denser during dry climatic periods and declining as a wetter climate returned"*. Comparison of reconstructions of Holocene climate change in the North Atlantic region (O'Brien *et al.* 1995, Bond *et al.* 1997) and Scotland (Chambers *et al.* 1997a, Anderson *et al.* 1998, Langdon and Barber 2003, Tipping *et al.* 2006) indicate that the region has experienced more significant climatic changes than the one that appears to have had the most impact on pinewoods. However, with the exceptions of Birks (1975) and Gear (1991), palaeoclimate reconstructions largely ignore the evidence of subfossil pine found in the peatlands themselves. The pinewood itself remains a significantly under-researched resource (Gear 1989, Daniell 1997, Leuschner *et al.* 2007, Tipping *et al.* 2007b).

Tree-rings have been well demonstrated as powerful research tools for climatological investigation (Jones *et al.* 1998, Briffa 2000). The longevity of some trees species indicates their robustness to change, while annual tree-rings can record patterns of change. Tree-ring series from near the timberline have in the past been found to be of exceptional value, both for climatic reconstruction and for identifying the consequences of climatic change to ecosystems (Fritts 1976, Tessier *et al.* 1997). There has only been limited dendroclimatological research on pine growing on Modern peatland surfaces, with just a few studies at local scale (Lundh 1925, Läänelaid 1982, Vaganov and Kachaev 1992, Linderholm 1999, Linderholm 2001) and in Sweden one regional scale investigation (Linderholm *et al.* 2002). It is important to know if Scots pine growing in peat can be useful in dendroclimatology. This is particularly applicable to Scotland which has such large areas of peat, much of which has been colonised or commercial grown with Modern Scots pine and also contains Holocene subfossil pine.

One of the aims of this research is to determine the influence of climate on the growth of Scots pine growing on peat. The relationship between the annual radial growth of Modern Scots pine on peatlands and adjacent mineral soils with meteorological records of temperature, precipitation and NAO are examined. Modern pine growing on mineral soils are included to help evaluate the influence of water table on annual radial growth and to help establish whether there are differences between pine from the highly oceanic north west and pine from the drier parts of south eastern Scotland (Edwards and Mason 2006).

A significant advantage of subfossil pine in Scotland is that it is often found *in situ*; whereas the majority of the long subfossil pine chronologies for most of Europe are developed from *ex situ* samples (many from river gravels). In its original positions of growth, pine is particularly suited to multi-proxy investigations, calibrations of peat accumulation rates, dendroecology and palaeo-woodland reconstructions. The wide regional extent of subfossil pine helps climatic change to be identified. Radiocarbon dates suggest that the subfossil pine found beyond its current limit in Scotland is broadly contemporaneous. This suggests the pine should cross-match and might be crossdated to establish a precise calendar-dated chronological framework for the investigation of past climatic change. If short-term and possibly abrupt events of pine colonisation or retreat of mire surfaces in Scotland could be identified, they might increase our understanding of the influence of the North Atlantic as a climate forcing mechanism (Selten *et al.* 1999).

1.1 Modern Scots pine

1.1.1 Geographic location

Scots pine *Pinus sylvestris* L. is a sub-boreal species with a wide ecological amplitude (Burnand 1976). The northern limit of Scots pine is at 70º29' north in Norway and the southern limit at 37º north in southern Spain (Steven and Carter 1959). The western limit is at 7º west in north-west Spain (Vazquez 1947) although pine woodlands of unknown status exist further west in northern Portugal (Eliseu 1942); the eastern limit is at about 138º east, with a few trees further east, reaching the Pacific coast (Malev 1955).

Temperature probably determines the southern and northern limits of *Pinus sylvestris* L, but at what stage of life this operates remains unclear. Pine does not occur naturally where mean summer (July) temperature is more than 26.7ºC (Carlisle and Brown 1968). Printz (1933) suggests that the southern limit of Scots pine may be determined by an unfavourable balance between photosynthesis and transpiration at high temperatures. The modern distribution range of Scots pine is combined with gridded annual precipitation and January temperature (New 1999) to show that in Europe the species lies between about 400 to 1500 mm yr^{-1} and about -18 to +8°C (Figure 1). The species experiences its coldest winter temperatures in Eurasia (Rehfeldt *et al.* 2002).

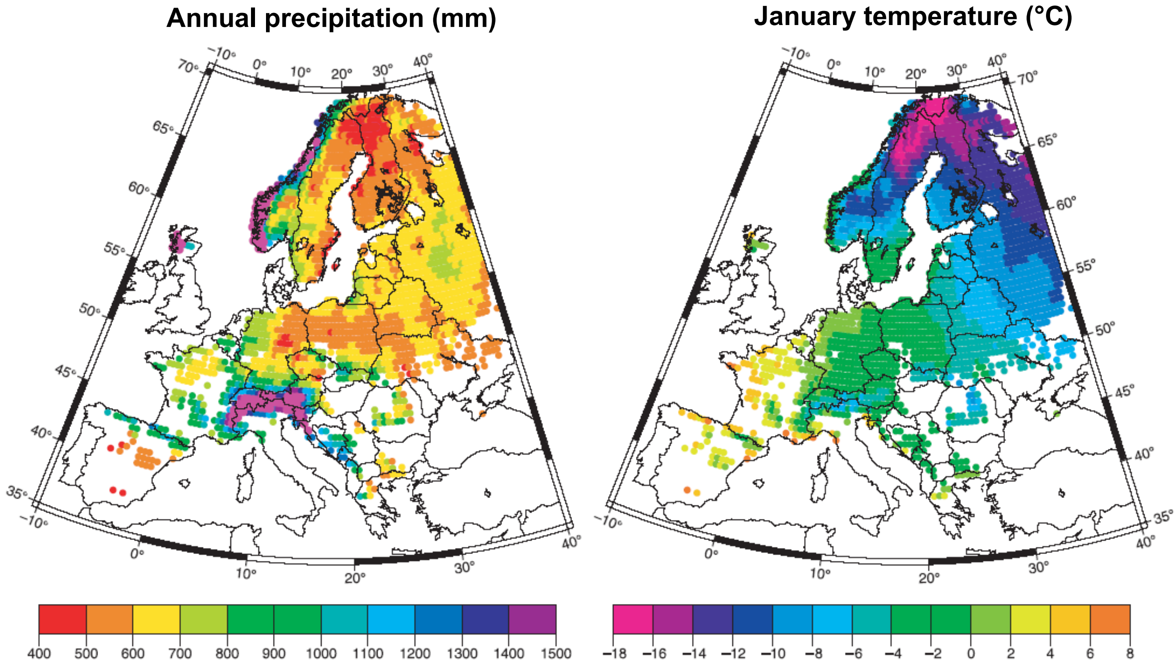

Figure 1: Present-day range of native *Pinus sylvestris*.
Obtained from Flora Europaea (Jalas and Suominen 1964) and a local flora (http://junon.u-3mrfr/msc41www/), with gridded annual precipitation (left) and January temperature (right). Source (Cheddadi *et al.* 2006)

1.1.2 Caledonian Pine Forest

The Caledonian forest in Scotland is a relict population of indigenous Scots pine and designated a special area of conservation under the amended European Union's Habitats Directive. In the UK the majority of this habitat corresponds to the National Vegetation Classification type W18 *Pinus sylvestris* – *Hylocomium splendens* woodland (Rodwell 1991). Exploitation has reduced the habitat to a small remnant of about 19,800 ha in Scotland (Mason *et al.* 2004b). While Caledonian forest occurs only in Scotland, it is part of the pinewoods that on impoverished acid sands and drier peaty soils extends across the

Boreal region of northern Europe. The main ecological zones in Europe are classified by Bohn (2000), Caledonian pine forest falls within the two zones described below:

> **Boreal Coniferous Forest** *occurs in some parts of Norway, most of Sweden, nearly all of Finland, northern Scotland as well as the southern part of Iceland. The western part of this zone has a cool-temperate, moist oceanic climate. Mean annual temperature is generally low and ranges from 8°C in Scotland to just above 1°C in the northern parts of the Russian Federation. Precipitation ranges from more than 900 mm in the west to 400 mm in the east, with extremes of 1200 and 300 mm. A short growing period (less than 120 days) is characteristic. Evaporation is low and prolonged periods of drought are rare. Snow generally covers the ground for several months during the winter.*
>
> **Temperate Oceanic Forest** *covers the British Isles except for the Scottish Highlands and the mountainous regions. In Scandinavia, all of Denmark, southernmost Sweden and a narrow strip along the coast of Norway are included. Additionally, some climatically sheltered fjords up to 64° north belong to this zone, where the climate is influenced by the Gulf Stream and the proximity to the ocean. The average annual temperature ranges from 7° to 13°C and annual rainfall varies from 600 to 1700 mm. In coastal areas the temperature of the coldest month does not fall below 0°C, inland mean temperature is locally below 0°C.*

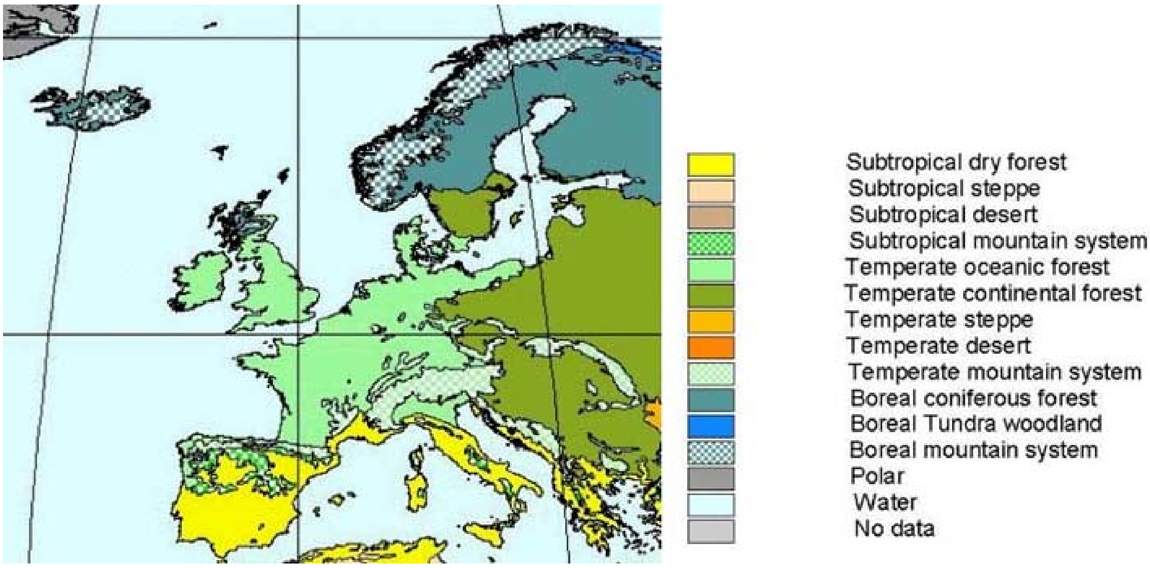

Figure 2: Europe ecological zones (Bohn and Neuhäusl 2000).
Sourced and adapted from (www.fao.org)

1.1.3 The ranges of Scots pine in Scotland

Carlisle and Brown (1968) state: "*Pinewoods of undoubted native origin in Britain are located in Scotland between the latitudes of 57º57'- 56º22' north and longitudes of 2º53'- 5º38' west* (Figure 3). Scots pine in Scotland at 5°38' west forms the western limit of the distribution of the species in northern Europe (Ennos 1991). Steven and Carter (1959) describes the latitudinal distribution of the existing native pinewoods in Scotland from 57°57' north at Glen Einig (15 km south-west of Lairg) to 56°22' north at Glen Falloch (60 km north of Glasgow). Pine do occur further north, on islands in Loch Assynt (30 km north of Ullapool) and about 15 km north-west of Glen Einig, but based on old parish records these locations were seeded from 18th century plantation. The most easterly native pinewood is 2°53’ west, at Glentanar (50km east of Aberdeen) and the most westerly 5°38’ west at Shieldaig (23 km east of Kinlochewe).

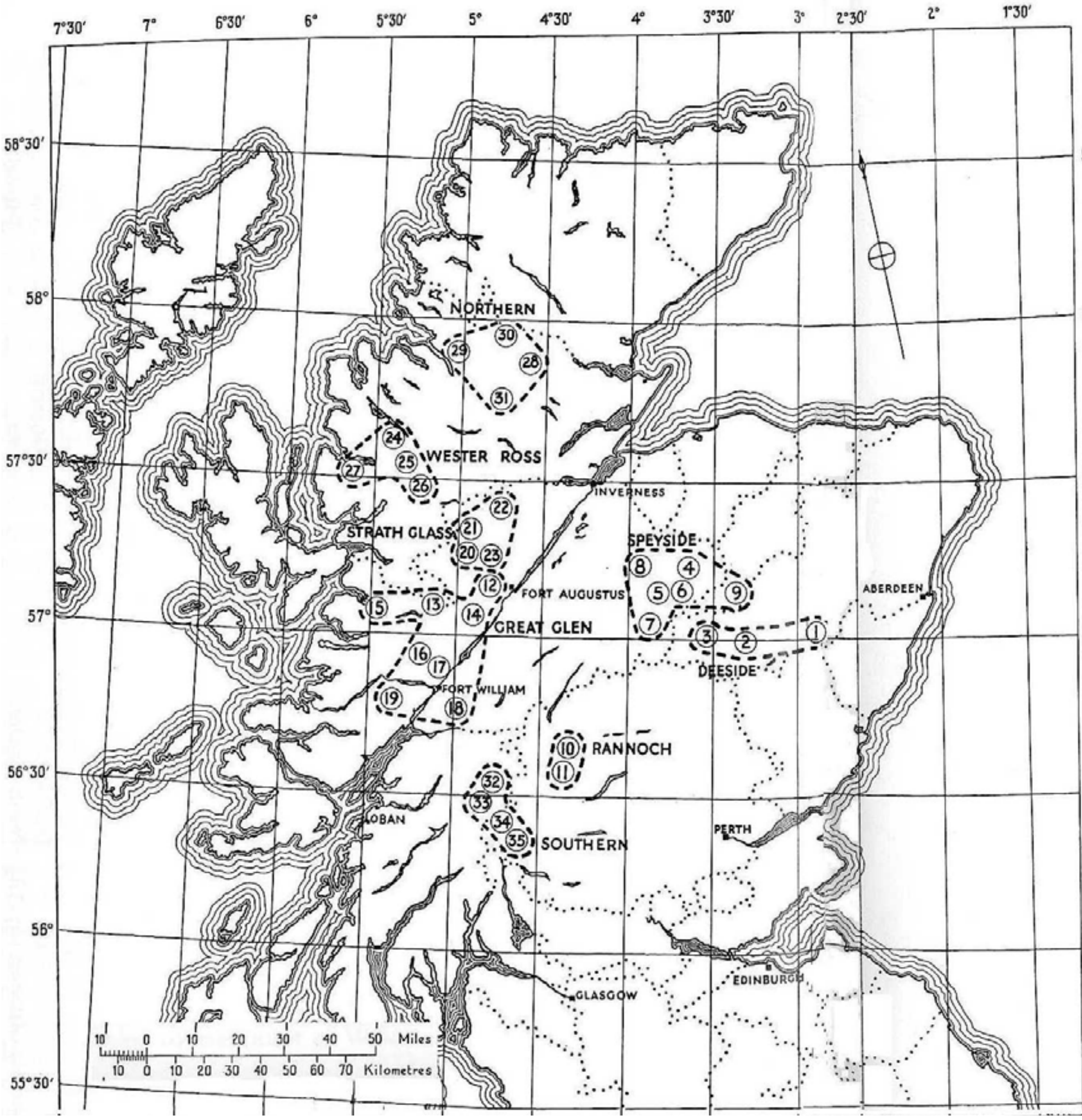

Figure 3: The native distribution of Scots pine in Scotland (adapted from Steven and Carlisle 1959).

Deeside	1. Glentanar, 2. Ballochbuie, 3. Mar.
Speyside	4. Abernethy, Rothiemurchus, 6. Glenmore, 7. Glen Feshie, 8. Dulnan, 9. Glen Avon.
Rannoch	10. Black wood of Rannoch, 11. Old wood of Meggernie, Glen Lyon.
Great Glen	12. Glen Moriston, 13. Glen Loyne, 14. Glengarry, 15. Batisdale, 16. Lock Arkaig and Glen Maillie 17. Glen Loy, 18. Glen Nevis, 19. Ardgour.
Strath Glass	20. Glen Affric, 21. Glen Cannich, 22. Glen Strathfarrar, 23. Guisachan and Cougie
Wester Ross	24 Loch Maree, 25 Coulin, 26, Achnashellach, 27. Shieldaig.
Northern	28. Amat, 29. Rhidorroch, 30. Glen Einig, 31 Strath Vaich.
Southern	32. Black Mount, 33. Glen Orchy, 34. Tyndrum, 35. Glen Falloch.

The highest find of Scots pine was on Ben Macdhui at about 840 m and a natural tree line on Craig Fhiaclach at about 615 m, both sites located in the Cairngorms. The altitudinal limit is higher in the south-east and central Scotland than in the more oceanic north-west. Recent research near Cairn Lochan in the northern Cairngorms found pine growing up to 830m (French *et al.* 1997). The altitudinal limit of Scots pine is probably determined by a combination of temperature and exposure to wind blast (Carlisle and Brown 1968). Pears (1969) highlights an important factor regarding the absence of pine at high altitudes in the Cairngorms. He states that *“an increase in altitude to approximately 600 m is often* *sufficient to double the effective local annual precipitation which results in a relatively wet mire and the exclusion of pine trees from the bog surface, but not necessarily from drier/steeper substrates".* French *et al.* (1997) found that increasingly severe microclimates above 600 m stunts the vegetation and creates gaps for pine seedling establishment. At higher altitudes, the severe climate appears to affect pine establishment more directly, so that nearly all young pine above 700 m altitude are found in sheltered microclimate sites (Grace 1989).

In Scotland the east is drier, lower, and consequently warmer and receives more sunlight than the west. Topography modifies precipitation, temperature and wind causing weather conditions in mountain areas to change from one valley to another. Wind is a critical climatic element which exerts serious detrimental effects on commercial forestry in the uplands of Scotland (Miller 1985); however this factor has been rarely considered in either dendroclimatic or palaeoclimatic studies. Scandinavian research identifies the overriding influences of latitude (i.e. day length) and altitude on the phenology and growth of pine (quoted in Ennos (1998)). There is also a tendency for the native Scots pine woodlands of Scotland to be located on slopes with a north-facing aspect (Steven and Carter 1959), where less favourable climatic conditions increase the competitive power of pine against birch. McVean and Ratcliffe (1962) developed a theoretical limit for pine based on the known present distribution of woodland types together with their ecological requirements, pollen analysis, subfossil remains and recorded history. They suggested that, free from human interference, Scots pine would spread north along the east coast as far as Berriedale and the Langwell Water, and inland north-westwards along the major valleys, (Figure 4).

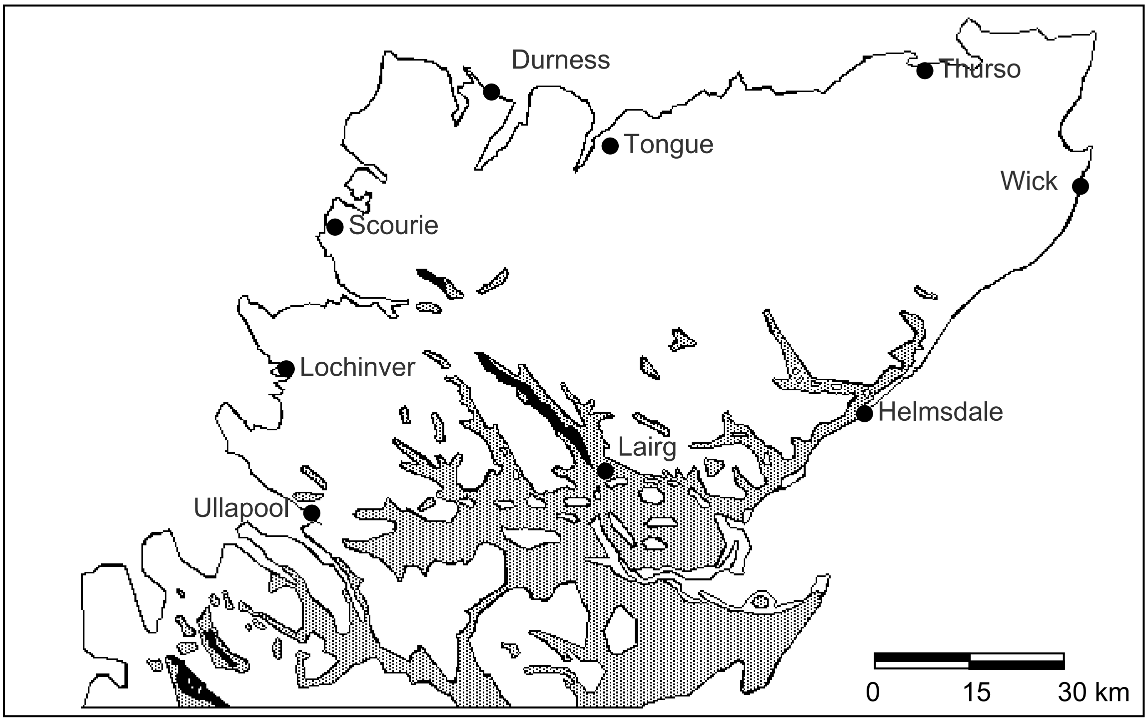

Figure 4: The theoretical northern limit of Scots pine (*Pinus sylvestris* L.).
The shaded area represents the theoretical limit, the black area major lochs (adapted by Daniell (1997) from McVean and Ratcliffe, 1962).

1.1.4 Natural regeneration

The life of a pine tree is a cycle of complex component processes occurring over years, from the initiating of flowers and dispersal of seed to the survival or mortality of the established tree. The success of each process is dependent upon environmental factors. These can be divided into: climate factors, such as temperature, humidity and radiation regimes during the growing season, and ground factors, such as soil moisture, depth of humus layer and soil texture affecting the water and nutrient availability at the soil surface and in the soil horizon. Latitude and altitude have a strong correlation with regeneration. In Sweden, Tegelmark (1998) found good regeneration in stands of Scots pines between latitudes 58º and 60° north and below 160 m altitude and poor results from stands further south or north and above 200 m altitude.

Ellenberg (1988) calls Scots pine one of the most *"drought resistant and frugal tree species in central Europe"*. Scots pine has the properties of a pioneer species, able to colonise and remain in a harsh habitat at the extreme of its range, Tessier (1986) suggests the name *"durable pioneer"* to describe this strategy. Scots pine at the tree line produce seeds when they are 20 years old (Carlisle and Brown 1968). Typical of pioneer species, pine needs good light for regeneration and growth and so is less competitive in mixed stands (Landolt 1977). Mikola (1962) states that Scots pine needs mean temperatures of +10.5ºC and +8.5ºC in the four summer months to ripen seeds and produce vegetative growth respectively. McVean (1963b) states that most seeds are distributed between April and June, the optimum temperature for germination is 21°C and that germination takes place more rapidly in light than darkness. McVean also identifies that germination takes place between March and September, with the greatest concentration in May. Modern forestry studies have identified regeneration of pine in the forest-limit zone requires at least two consecutive summers warmer than the "average" which at present occurs probably only a few times in a century (Sirén 1961).

A survey of pine in the northern Cairngorm mountains identified the criteria: distance from forest (the main seed source), altitude, vegetation (type and height), drainage and soil organic horizon depth as the main factors affecting pine colonization (French *et al.* 1997). Combining these effects, pine establishment was identified as greatest close to a forest between 600-700 m, in *Calluna vulgaris* moor or lichen-rich dwarf *Calluna* heath, on well drained mineral soils with at most a shallow organic horizon. An increase in moisture is likely to cause pine to become restricted to better drained slopes. Establishment at low altitudes tended to be restricted by deep, wet peat and tall vegetation and at high altitudes mainly by climate. Increased light intensity at the forest floor through tree death is known to influence Scots pines seedlings height growth and survival (Chantal *et al.* 2003, Mason *et al.* 2004a). Michie (1901), cited in Steven and Carlisle (1959) in discussing pinewood dynamics in Ballochbuie, states that *"pine has a tendency only to regenerate in the open and so these woods gradually move across the landscape over time"*. An important implication highlighted by Edwards (2006) is that in Scotland pine does not readily regenerate under its own canopy.

1.1.5 Disturbance of native pinewood

The oldest Scots pine trees recorded in Scotland are 550 years old at Glen Loyne, Invernesshire (Bartholomew *et al.* 2001), and 430 years at 450m in Creag Fhiaclach, in the Cairngorms (Grace and Norton 1990). These compare to a Scots pine of 700 years identified in Sweden (Engelmark *et al.* 1994). Although significant correlations occur, neither tree-height nor tree diameter at breast height appear to be useful in calculating the age of Scots pine trees in Scotland due to too much scatter (Nixon 1996, Arkle and Nixon 1996, Goucher and Nixon 1996, Edwards and Mason 2006). Hughes (1987) describes the general structure of trees of stands over 180 years of age as open with a preponderance of older trees. Most remnant stands of native pinewood have developed as a consequence of management. Exploitative fellings (Steven and Carter 1959), conversion to deer forests (Watson 1983) and felling during the First and Second World Wars (Mason *et al.* 2004b) have often influenced the structure and composition of pine woodland growing today in

Scotland. Scott (2000) showed that from germination a period of 20-25 years was required for trees to reach a height of 1.5 m in the Ballochbuie pinewood. However the full effects of cultivation and browsing control on the long-term development of stand structure have yet to be explored. Direct manipulation of the vegetation and soil through weed control and /or cultivation increase regeneration recruitment (Booth 1984, Low 1988, Worrell 1990), but highlight that control of browsing is essential for successful establishment (Miles and Kinnaird 1979). Grazing animals may have two opposing effects on the development of tree cover. Browsing suppresses the emergence of tree seedlings from ground vegetation cover. However, trampling damage may play an important role in breaking the mat of vegetation and provide micro-sites for seedling establishment (Legg *et al.* 2003).

Modern ecological studies of the boreal forest in America, Europe and Asia have shown 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* (Carlisle and Brown 1968, MacKay 2004) and similar associations have been inferred for this taxon from palaeoecological records (Bradshaw and Zackrisson 1990, Lageard *et al.* 2000). *Pinus sylvestris* is not classed as a "fire pine", with adaptations such as serotinous cones which remain closed unless the heat produced from fire opens them (Whelan 1995), but in Eurasian boreal forests the genus is regarded as the most fire-adapted of trees, with thick bark, especially under dry conditions (Agee 1998). After fire, surviving trees provide the seed source for post-fire regeneration. Seedling establishment after fire is generally low initially and regeneration becomes more abundant 3-5 years later (Engelmark 1993, Schimmel 1993). One reason for this is that *Pinus sylvestris* does not form a seed bank and there is considerable year to year variation in seed crop (Koski and Tallqvist 1978).

1.1.6 Genetics and genetic local adaptation

At around 5000 BC (well after the founding of the Scottish populations of Scots pine), Britain became an island and the climate turned much more oceanic in nature. In the absence of gene flow from continental Europe there was the opportunity for natural selection to occur on the Scottish gene pool. Over the 50 generations or so after the population's isolation, a race locally adapted to the oceanic conditions and genetically differentiated from the populations on the continent was produced (Ennos *et al.* 1997).

Studies on the terpenes in pine resin have shown biochemical differences between pinewoods which are an expression of genetic differences (Forrest 1992, Kinloch *et al.* 1986). The pinewoods of the North-west zone, near Kinlochewe, and those of the South-west zone around Fort William are the most genetically distinct groups. Work with genetic markers has involved analysis of mitochondrial DNA variation, variation which can only be transferred between populations by seed (not pollen). A study on twenty Scottish populations of Scots pine (Ennos *et al.* 1995) detected two mitochondrial DNA types (mitotypes). Mitotype **a** is found in all Scottish populations (including relevant to this study Loch Maree, Glen Affric and Abernethy), and in most of these it was the only mitotype present. However, in three populations located in the west (which includes Shieldaig), a second mitotype **b** is found.

Both genetic study (Ennos *et al.* 1997) and a palynological synthesis (Birks 1989) state that there is strong evidence in favour of two difference origins for the modern Scots pine. These studies conclude, however, that a glacial refugium in northern-central Europe, from which modern Scots pine have originated, is probable, but an endemic refugium in Scotland remains a matter of debate. A genetic survey carried out on mitochondrial DNA from fossil pollen and macro remains identifies the geographical distribution of the three haplotypes of *P. sylvestris* in Europe are consistent with a population of common origin from northern Europe (Cheddadi *et al.* 2006).

Provenance origin is important for survival. Research on a restricted number of populations indicated genetic differences in growth rates and resistance to the indigenous rust pathogen *Peridermium pini* in native populations of Scots pine. When tested in the east, a population from Loch Maree grew more slowly and showed a much higher incidence of *P. pini* infection than did populations from Eastern Scotland (Lines and Mitchell 1964, Ennos 1991). In more recent research on seedlings planted at a single site near Edinburgh (Ennos and Perks 1995), bud burst was found to be one week later in the population from Abernethy, compared to the other three populations from Loch Maree, Glen Affric and Rannoch. Despite the limited size of the trail, bud burst is of particular interest because of its adaptive relevance and because it is a characteristic that does not alter with age (Perks and Ennos 1999).

1.1.7 Pine trees growing on bog

Scots pine seeds prefer well-drained mineralized soils for germination. Waterlogged seeds, or seeds buried just below the surface of very wet soil, fail to germinate (McVean 1963b). Bogs, because they usually receive nutrients only from precipitation, are *oligotrophic* (poorly fed) and represent one of the most nutrient-poor and acidic environments in the British natural landscape (Lindsay 1995). In continental Europe a large proportion of bogs are naturally wooded (Moore 1984), but in the UK this is uncommon (Ellenberg 1988). Currently the majority of relatively undisturbed bogs in the UK are treeless, including the extensive blanket bogs and mires of Scotland. Whether this is a natural state has only recently begun to be examined. The National Vegetation Classification (Rodwell 1991) takes little account of Scots pine in mire communities. However, increasingly pine is being recognized as a widespread component of the bog communities of Scotland. At Abernethy in Strathspey, Legg (2003) found Scots pine to be an almost ubiquitous constituent of bogs, present in any of the M15, M17, M18 and M19-type[1] bog communities, if the conditions are right. Bog woodland is a rare habitat in the United Kingdom, broadly defined by areas of trees growing on peatlands where the high water table and low fertility restrict tree growth. It has the appearance of open woodland, where scattered trees grow on a bog in a relatively stable ecological relationship and without the loss of bog species (Wells 2002).

Bog vegetation is particularly sensitive to climate because water and nutrient supply is via atmospheric precipitation. Godwin (1956) first suggested that Scots pine may have grown on the surface of bogs ever since their formation, becoming denser during dry climatic periods and declining as wetter climate returned. There is overwhelming evidence that the primary factor in determining the distribution of trees on bog is waterlogging. The growth of trees in mire strongly depends on the depth and fluctuation of the local water table (Boggie 1972). High water tables may depress growth, as nutrients become less available in poorly aerated soil (Mannerkoski 1991); significant lowering of the water table may cause trees to experience water stress (Dang and Lieffers 1989).

Legg et al. (2003) found the tree growth, size and their density appear strongly associated with the water table, which led them to postulate that a lowering of the water table might result in some of the drier bogs, or parts of a bog, being invaded by trees. This view is supported by the common observation of the colonization of bogs by trees following

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[1] M15 (*Scirpus cespitosus – Erica tetralix* wet heath), M17 (*Scirpus cespitosus – Eriophorum vaginatum* blanket mire), M18 (*Erica tetralix – Sphagnum papillosum* raised & blanket mire) and M19 (*Calluna vulgaris – Eriophorum vaginatum* blanket mire) categories of the National Vegetation Classification (Rodwell 1991)

changes in the drainage pattern, with the loss of bog community. Additionally, bogs often display a graduation of trophic status from central, true ombrotrophic cores, through to marginal lagg fen. The wettest part of a bog other than the surrounding lagg fen is generally found on the highest part of the dome (Ingram 1983). A well developed raised bog has a lagg which represents a narrow wet zone, approximately 10 m wide, where bog-water meets water richer in minerals derived from the surrounding mineral soils (Franzén 1987). Marginal slopes of bog are better drained, where the annual fluctuations of the water table are greater, and where well-aerated peat is present for longer periods, as a result denser stands of taller trees are typically located near bog margins. The longest dry conditions experienced by peat bog during its development are the major determinants of its final height and curvature, which can be described using standard shapes from soil hydrophysics (Ingram 1982).

There is very little lateral flow of water across the surface of bogs. So in the absence of changes in drainage, the water table variation is determined largely by the balance between rainfall and evapotransiration (Lindsay 1995). Temperature may influence tree growth both directly through growth season temperature and indirectly through regulation of the water table by evaporation (Mannerkoski 1985). An increase in rainfall/or decrease in evaporation is therefore likely to result in waterlogging of some areas of woodland and reversion to bog. Smaller-scale drainage has also taken place on many bogs in the past, usually associated with grazing. Apart from water logging there are a number of other unfavourable conditions that hinder the establishment of Scots pine on peat (Birks 1975). Nitrogen and Potassium are very deficient. Heather may produce inhibitors of the mycorrhizae (mycorrhizae help young seedlings). Modern cultivation studies on Corsican pine demonstrate that disruption of *Calluna*-dominated vegetation by a rather deep furrow line, complete cultivation (or burning of the surface), followed by a single substantial application of a phosphate fertilizer at, or soon after, planting assists establishment (Fourt *et al.* 1995).

Mackenzie & 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. Most bog pine communities today are located in the east, particularly on the northern flanks of the Cairngorms, which are described by Stevens & Carlisle (1959) and McVean & Ratcliffe (1962). In the west, good examples are located at Glen Affric and near Loch Maree. Similar communities from other areas of Scotland are summarised by MacKenzie & Worrell (1995). Tree growth appears to be constrained by relative drainage of the upper layers of peat rather than absolute peat depth (Wells 2002). Bog woodland is least likely to burn (Schimmel and Granström 1991) and it is possible to find pine woodland on bog that has not been affected by forest fire for several hundred years (Ågren and Zackrisson 1990).

1.2 Holocene Scots pine in the peatland archive of Northern Scotland

The peatlands of Northern Scotland are one of the largest and most intact areas of blanket bog (a globally rare ecosystem type) in the world (Stroud *et al.* 1987). Their outstanding importance, both nationally and internationally, lies in their total extent, continuity and diversity. The unusual feature of mire systems is that a record of the sites development is preserved within the peat archive, and in many cases this record can extend back over many thousands of years. Mires preserve a record of pollen rain, which has enabled palynologists to reconstruct vegetational history. A growing understanding of the relationship between peat archives and climatic patterns of the past, together with their potential to preserve chronological information, means that an increasingly significant proportion of research into recent climate change is being centred on mire systems. Peat normally preserves in stratigraphic order and in a radiocarbon datable deposit, environmental information significant for the investigation of climate change. The preservation of pollen rain in peat has enabled palynologists to reconstruct the vegetational history. Peat can also preserve organic and inorganic anthropogenic remains such as: settlements, tombs, field systems (Caulfield *et al.* 1998), track ways (Morgan *et al.* 1987), implements and bodies.

Extensive horizons of subfossil pine in Northern Scotland indicate that occasionally the peatland environment became suitable for the mass colonisation of pine, subsequently followed by conditions which preserved pine. Numerous studies have confirmed subfossil pine as an important source of detailed palaeoecological and palaeoclimatological information. However the dendroclimatological potential of widely occurring and possibly broadly synchronous horizons of Holocene pine preserved in the peatlands of Scotland, as elsewhere (Chambers *et al.* 1997b), has been largely ignored. This chapter reviews the narrow climatic time window that peatland development occupies and examines the relationships between pine preservation and climate.

1.2.1 The relationship between peatland and climate

The multitude of terms and inconsistencies in definitions complicates the study of peatlands. Definitions used in recent European literature (www.peatlandsni.gov.uk) are used throughout this study:

- Peatland - an area with a naturally accumulated peat layer at the surface
- Mire - a peatland where peat is currently forming and accumulating
- Bog - a peatland which receives water solely from rain and/or snow falling on its surface
- Fen - a peatland which receives water and nutrients from the soil, rock and groundwater as well as rain and/or snow

The term "peatland" is preferentially used so as to include Scots pine that are preserved in, or grow on, all peat masses (whether these are active or not). The term mire while encompassing fen, as well as raised, blanket and intermediate bogs (ombrotrophic peat masses) i.e. receive all their water input as precipitation (Lindsay 1995), was considered not to include trees located in moribund (inactive or non peat forming) mire. The term peatland allows for the status of mire to change with time, from infilled lake/loch with fen peat, to moribund and degraded state. It is also used to encompass pines in "bog woodland" a term also used in the European legislation, but one appeared to be intended to be applied to a much wider spread of mire types than simply ombrotrophic ones (Wells 2002). Similarly, here the term “bog pine” is used to encompass Scots pine growing on (active) mire, bogs or fen.

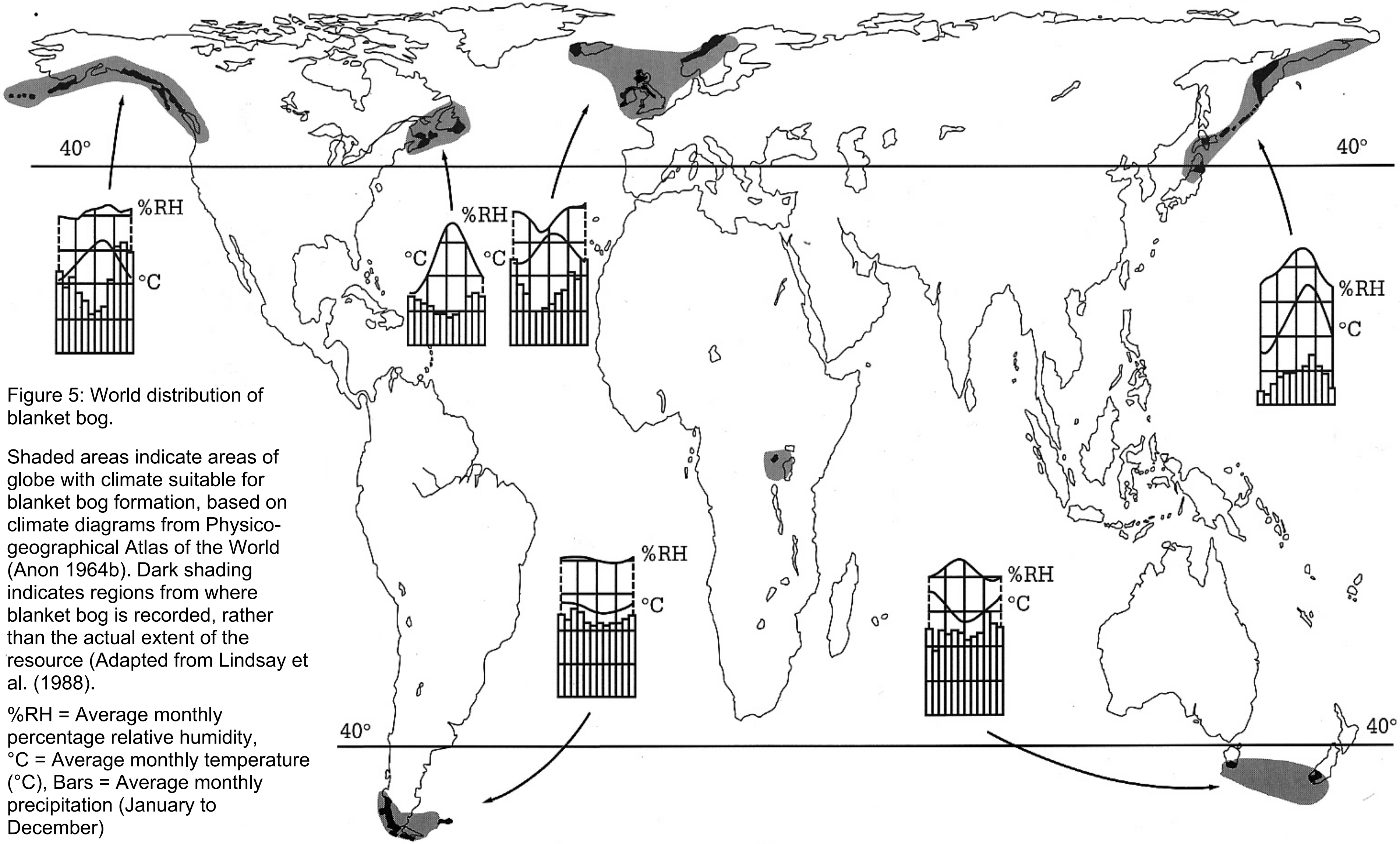


Figure 5: World distribution of blanket bog.

Shaded areas indicate areas of globe with climate suitable for blanket bog formation, based on climate diagrams from Physico-geographical Atlas of the World (Anon 1964b). Dark shading indicates regions from where blanket bog is recorded, rather than the actual extent of the resource (Adapted from Lindsay et al. (1988).

%RH = Average monthly percentage relative humidity,
°C = Average monthly temperature (°C), Bars = Average monthly precipitation (January to December)

Lindsay (1988) summarises the combination of conditions generally regarded as necessary for blanket peat as:

- a minimum annual rainfall of 1000 mm;
- a minimum of 160 wet days;
- a cool climate (mean temperature less than 15°C for the warmest month) with relatively minor seasonal fluctuation (mean annual temperate range of 9-15°C).

Absolute temperatures also need to be sufficiently high so as not to limit the growing season through prolonged winter, but sufficiently low during summer so that the decomposition of plant remains is not too rapid. These conditions occur mainly in the oceanic regions of cool temperate zones (Figure 5).

A combination of wet days and mean annual temperature (Figure 6 and Figure 20 respectively), appear to isolate two climatic factors that favour the development of blanket bog. Goode and Ratcliffe (1977) identify the geographical limits of blanket bog in Scotland with the isoline of 160 wet days (a “wet day” being a period of 24 hours with precipitation of at least 1 mm). The map of mean annual number of wet days (Figure 6), regarded as the best ecological index of precipitation, shows that virtually the whole region of Northern Scotland currently has more than 160 wet days and favouring the development of blanket bog. Scotland has 10,562 km^2 of blanket bog (Lindsay 1995). Converse to expectations, high mountains which produce the heaviest rainfall are much less conductive to the development of blanket bog, due to the reduction of extensive waterlogging caused by topography.

Bogs are ombrotrophic, which means that they are formed by plants which are completely dependent on rainwater and nutrients brought by precipitation. This dependency on atmospheric input in the form of precipitation, temperature and wind, which affects the humification of peat, makes bogs well suited for recording climatic variations, and can hence be viewed as proxy data (Barber 1982, Blackford 1993, Blackford and Chambers 1995). The two most northern districts of mainland Scotland, Caithness and Sutherland contain the largest continuous expanse of blanket bog in Britain, with a total extent of 4000 km^2 (Lindsay *et al.* 1988). This is important as one of the most extensive peat archives anywhere in the world, but its value is perhaps most significant in terms of palaeoclimate research due the considerable influence of the North Atlantic Ocean through the Gulf Stream current and the Westerly wind across the regions. Changes in North Atlantic thermohaline circulation is considered one of a possible number of climate forcing mechanisms whose relative importance and interplay during the Holocene period is poorly understood (Rind and Overpeck 1993, Stuiver *et al.* 1995, Schulz and Paul 2002).

Lindsay (1995) describes the catotelm as the accumulation of dead plant material which gives the bog its overall shape and which may be up to 10 m deep. Hydrological processes within the catotelm are very slow. The thin protective surface layer of a bog/mire, sealing the catotelm from the atmosphere, is termed the acrotelm, which is usually no more than 30 cm deep. Hydrological processes in this layer are extremely rapid, with rates of water flow up to 1000 times greater than those recorded for the catotelm (Ingram and Bragg 1984). Schouten *et al.* (1992) state that the water table lies at or very near the surface in spring, but falls below it during the remainder of the year.

1.2.2 Problems of temporal resolution

The history and status of the Scottish pinewoods and their relationship with climate is a long-running topic of research (Bennett 1995) that remains unresolved in many aspects.

While increasingly multiproxy studies and inter-site correlations have helped develop our understanding, particularly of regional variability, little real refinement has been made in dating the climatic transitions of the Holocene beyond identifying that some occurred "abruptly", possibly over a decade to a century timescale. For decades, attempts to elucidate the timing of Holocene climatic change in Scotland have relied predominantly on palynological evidence, whose reliability may be questioned due to intrinsic problems:

- long-distant transport & vertical displacement of *P. sylvestris* pollen.
- fossil stomata reveal the presence of *P. sylvestris* up to 1600 years prior to the dates indicated from pine pollen levels used to interpret its local presence (Froyd 2005).
- short periods of local occurrences of pine can be missed (Charman 1994)
- a discrepancy of up to about 700 years between the ^{14}C ages from wood and those from peat. This has attributed to contamination of peat samples with younger material (Gear and Huntley 1991).
- in the absence of high-resolution dating to constrain peat growth rates and possible hiatus, interpolated dates are subject to unknown error.

P. sylvestris is a prolific producer of pollen which is readily dispersed over long distances, therefore the presence of pine is difficult to identify and the best evidence is preserved macro-fossils from the trees themselves. High resolution pollen analysis of peat assumes there has been negligible movement of pollen grains, but the work of Butler (1992) suggests that there may be considerable vertical displacement in peat and other sediments. The fossil stomata of *P. sylvestris* provide unambiguous evidence for the past local presence of pine (Froyd 2005). Recent analysis of fossil stomata has demonstrated further problems with pollen analysis where the postglacial presence of Scots pine at two sites in the Scottish Highlands has been identified 1600 and 600 years earlier than the arrival indicated by traditional palynological methods (Froyd 2005). This research also reveals the presence of Scots pine where pollen frequencies are as low as 0.4%, well below the 20% minimum frequency threshold commonly adopted. This highlights that it is possible for Scots pine to be present for hundreds to thousands of years before a local population is registered in the palynological record.

Bennett (1984) highlighted a common discrepancy between low pollen records which indicated the absence of local Scots pine and the widespread occurrence of pine stumps preserved in blanket peat. Wilkins (1984) noted a similar contradiction between the pollen record and occurrence of preserved stumps on Lewis. The occurrence of subfossil Scots pine stumps in many areas of Scotland, apparently without pollen evidence, well illustrates a problem caused by poor stratigraphic resolution. The contradiction has now been explained, at least in part, by the general lack of sampling resolution in pollen diagrams (Charman 1994).

Mighall (2004) found wood pieces with a radiocarbon date of 4485 ± 70 uncalibrated ^{14}C yr BP (uncalibrated ^{14}C yr BP are uncalibrated years before present (1950) radiocarbon assays), which were older than the age of the peat (4160 ± 50 uncalibrated ^{14}C yr BP) at the same level and thought to be contemporary. Wilkins (1984) also identifies a ^{14}C dated pollen maximum as 500 years earlier than preserved stumps. Reid and Thomas (2006) identify two occurrences of peat about 500 years younger than the charcoal on its upper surface. Reid and Thomas state that "*since the humin-only charcoal dates are likely to be more accurate than the mixed-fraction peat dates, both reversals are probably attributable to translocated carbon producing anomalously young peat ages*". The too young radiocarbon age estimates are caused by the transport of young carbon downwards by the roots of mire plants (especially sedges), although downward water flow may also contribute (Charman *et al.* 1992). These accounts reinforce the about 700 year discrepancies between the ^{14}C ages from wood and peat which are reported by Gear (1991). Conversely, Olsson (1986) found peat 500 years too old in comparison to charcoal from contemporaneous layers in peat bog. However, radiocarbon dating of charcoal merely dates the time of growth of the tree-rings that yielded the charcoal. Charcoal derived from the heartwood of an old tree, or reused timber, may pre-date the fire by hundreds of years (Baillie 1995a).

Although a commonly applied method of dating, radiocarbon dating is imprecise (Baillie 1990, Pilcher 1991b). Shore (1995) further describes some of the problems encountered with the ^{14}C dating of peat, but there have been few detailed studies. A problem of the imprecision of radiocarbon dating is the temptation to “suck in and smear” dates into the same event (Baillie 1991). Even wiggle-matching (Van Geel and Mook 1989) of contiguous peat layers containing a band of charcoal cannot pinpoint its age to better than a half-century (Chambers *et al.* 1997b). In view of these problems, where possible radiocarbon dates from pine macro-fossils are used in preference to those from peat.

Time parallel markers, such as tephra isochrones, are one line of research which has been forwarded to overcome the inherent problems of reliance on radiocarbon dating to provide chronological control (Pilcher 1991a, Kilian *et al.* 1995, Speranza *et al.* 2000). Identifying and geochemically typing the tephra layers can enable precise correlations between sites on a regional scale (Langdon and Barber 2004). However, the occurrence of tephra are dependent on the spatial extend of the airfall events which often have patchy distribution (Dugmore *et al.* 1995a). Additionally, there are probably only about nine Holocene eruptions to act as markers in Scotland (Pilcher and Hall 1992). Also, except through dendrochronology and historical records, the dating of such markers largely relies on radiocarbon dating, and research by Charman *et al.* (1995) indicates tephra can move subsequent to deposition.

1.2.3 The preservation of Holocene subfossil pine

Subfossil refers to remains whose fossilization process has not been completed, either due to lack of time or because the condition in which they were buried were not optimal for fossilization. One of the most important differences between subfossil as opposed to fossil remains is that the former contain organic material, which can therefore be used for radiocarbon dating. Site hydrology plays an essential aspect to understanding the preservation of pine in the peat archive. Holocene wood is well preserved in mountain lakes and peat, due to anaerobic conditions (Bartholin and Karlen 1983). Birks (1975) and Pears (1975, 1988) conclude that the establishment and subsequent preservation of pine stumps is partly controlled by mire surface conditions. Topography often controls the hydrology of a site and hence the initiation and rate of peat accumulation. Pears (1969) concluded that the potential of a peat profile to record evidence for regional changes in climate was largely dependent on site specific factors (principally topography). Binney (1997) supports this hypothesis and presents evidence from humification analysis that the stratigraphic position of subfossil pine stumps corresponds to a shift to dry mire surface conditions, followed by a return to wet conditions. A rise in moisture and peat accumulation is expected to increase the preservation potential of subfossil pine, and so be related to their occurrence as extensive lateral horizons in the pine archive.

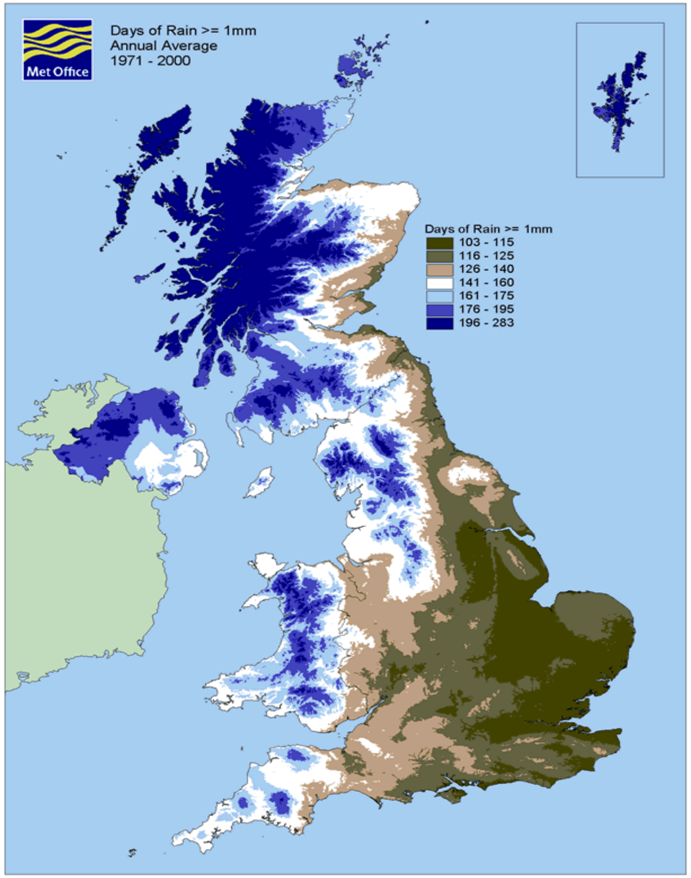


Figure 6: Days of rain >1 mm - annual average 1971 – 2000 in the United Kingdom. Source: Met Office (www.metoffice.gov.uk)

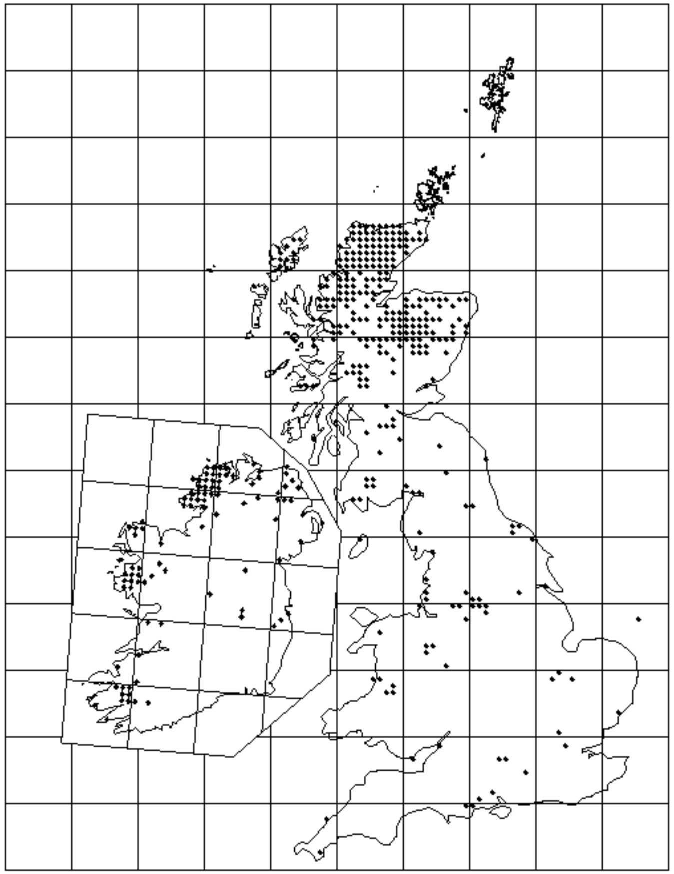


Figure 7: Occurrence of subfossil pine remains in the British Isles (Bennett 2005).

Regionally synchronous variations in water levels are thought to be climatically driven (Harrison and Digerfeldt 1993). Where peat depth above the water table is limited, trees may be sensitive to fluctuations in water level, and potentially may offer a high-resolution proxy indicator of lake-level. Daniell (1997) provides evidence that at some sites Holocene pine trees go into check from time to time due to lake-level fluctuations. This suggests that Holocene pine over a wide area might also provide a proxy indicator for rainfall.

Wooded bogs are thought to have been fairly widespread and common during the mid-Holocene period from 5000 to 2000 ^{14}C cal. yr BC, especially during the relatively dry climatic periods (MacKenzie and Worrell 1995). Prior to this, bogs were rare in Scotland because most mires were at the early stage of their development and their vegetation was largely minerotrophic (i.e., they were fens, not bogs). Comprehensive ^{14}C-dating reconstructions of peat in Scotland (Tisdall 2003) shows that blanket peat covered all but the steepest and most exposed landforms by 5100-4100 ^{14}C cal. yr BC. After about 7000 ^{14}C cal. yr BC there were a series of abrupt and mostly short-lived climatic shifts, to relative aridity and then increased rainfall, as well as some apparently corresponding but overall fewer shifts of temperature. Many of these climatic shifts appear to correlate with others in the North Atlantic region (Tisdall 2003). Cooler, wetter conditions occur from about 3,000-2,000 ^{14}C cal. yr BC which favoured paludification, and large areas of woodland appear to have been replaced by peatlands (Price 1983), however this loss may also have occurred due to human activities. Dupont (1986) identifies a marked wet phase between about 1700-1550 ^{14}C cal. yr BC and interpretes a drop in mean annual temperatures of 1°C between about 2000-1000 ^{14}C cal. yr BC.

Site ecology together with the timing and spatial patterning of Holocene Scots pine occurrences has yet to be examined in detail. The vast majority of recorded occurrences of Holocene pine in the UK have been in northern Scotland (Figure 7). Scots pine appears to be the sole species preserved in bogs in the north, oak tending to occur in lowland bogs (Steven and Carter 1959). Bennett (1984) suggests the taxon became largely excluded from non-peat substrates in England due to competition from range-expanding broadleaved taxa. Phases of drier conditions during the development of mires at Whixall Moss (Shropshire) and White Moss (Cheshire) are suggested to have provided ideal seedbed conditions for pine. These mosses demonstrate an apparent temporal segregation of subfossil oak and pine in distinct mire environments, while in contrast contemporaneous subfossil pine and oak phases occur on mires in Northern Ireland and also possibly the east of England (Chambers *et al.* 1997b).

1.2.4 The early history of Scottish pinewoods

Prevailing climatic conditions during the last glacial maximum restricted the range of pine in Europe to patchy, discontinuous and climatically constrained areas on the continent designated as glacial refugia (Bennett *et al.* 1991) from which they subsequently expanded. The severe conditions of the Younger Dryas ended abruptly about 9900 ^{14}C cal. yr BC, when rapid climatic warming marks the beginning of the Holocene Epoch. There was a time-lag between the conditions amenable to tree growth and the arrival of Scots pine, a lag induced by seed dispersal and probably also by distance from refugia (Huntley and Birks 1983, Birks 1989). *Pinus* pollen first increases in abundance in the Highlands about 6900 ^{14}C cal. yr BC, evident at sites from Western Ross (Birks 1972). Despite low pollen abundance during the early Holocene, a small number of macrofossils indicate sparse but local presence in the lowland fringes of the eastern Highlands (Vasari 1968). These occurrences are supported by macrofossil at 500 m in the eastern Cairngorms about 6200 ^{14}C cal. yr BC (Huntley *et al.* 1997) and in Abernethy Forest about 5900 ^{14}C cal. yr BC (Birks 1978). Forests dominated by native Scots pine in Scotland were at their greatest extent when they covered the Highlands by about 5,500-3,000 ^{14}C cal. yr BC (Bennett 1984, Bennett 1989, Bridge *et al.* 1990).

Above the latitude 58° north in mainland Scotland, there are few modern accounts of the vegetation history despite the abundance of peat deposits. Pegar (1979) indicates eastern Caithness to have been largely treeless for the whole of the Holocene. Charman (1994) concludes the same for eastern Sutherland with the exception of a brief phase of local pine forest between 2900-2350 ^{14}C cal. yr BC. Lack of tree cover in these regions has usually been attributed to adverse environmental conditions, including wind exposure, low temperature and insolation, storms, short growing season and salt spray (Peglar 1979). Pennington (1975) indicates south-west Sutherland had widespread pine forest until *about* 2000 ^{14}C cal. yr BC.

1.2.5 A 3500-2300 ^{14}C cal. yr BC northward expansion of Scots pine

In the Highlands of Scotland (above the towns of Ullapool on the west coast and Glospie on the east coast) and just beyond latitude about 58º north, the current ecological northern limit of Scots pine, (McVean and Ratcliffe 1962), a regionally widespread horizon of subfossil pine is preserved in Holocene peat. The widespread occurrence of subfossil pine which often becomes exposed through peat cutting has long been observed, e.g. Lewis (1905, 1906, 1908, 1911). Samuelson (1910) noted them and proposed that they represented a synchronous regional colonisation of the mire surface. Birks (1975) reinvestigated some of Lewis' Scottish pine stump sites with radiocarbon analysis; this indicated a wide range of dates and suggested they did not represent a synchronous invasion of the mire surface. However, it was concluded there was a cluster of mean dates between about 2500-2000 ^{14}C cal. yr BC. Gear (1991) obtained further radiocarbon dates for pine stumps collected from blanket peat in the Highlands, (as well as compiling previously published radiocarbon dates for similar material) and concluded that all the dates fell between about 3400 and 2200 ^{14}C cal. yr BC. These studies indicate a short-lived, but widespread expansion of Scots pine onto the peatlands of the Highlands of Scotland and their subsequent preservation in them.

With the principal exception of parts of Caithness, subfossil pine have now been recorded in almost every 10 km grid square of the national grid that lies to the north of the present natural range of the species and up to an elevation of 305 m on Ben Loyal, one of the most northernmost mountains in far northern Scotland (Huntley *et al.* 1997). Trees grew in areas very close to the exposed western and northern coasts, such as those close to Loch Vatachan and Melness respectively (Huntley *et al.* 1997); as with the localities on Lewis today, these areas are extremely wind-exposed and unfavourable for tree growth (Lamb 1964b). Scots pine stumps found in blanket peat indicates a widespread northward advance around about 3000 ^{14}C cal. yr BC. Pine extended beyond its former range-limit to the coast of Caithness (Birks 1975, Gear 1989, Charman 1992), to Lewis between 3700-2500 ^{14}C cal. yr BC (Wilkins 1984); (although Fossitt (1990) argued that pine was widespread from about 5500 ^{14}C cal. yr BC), to eastern Skye (Williams 1977, Birks 1983) and Rum (Durno 1967, Birks 1975). Then probably less than 1000 years later, there was a dramatic collapse in the extent of the native pine population throughout Scotland (Birks 1975, Bennett 1984, Bridge *et al.* 1990, Gear and Huntley 1991), as well as in isolated outposts in England (Bennett 1984) and in western Ireland (Bradshaw 1987). Only in the core areas of Speyside and the Cairngorms was natural pine woodland able to survive. The dates from these studies vary considerably. However, comparison of the re-calibrated radiocarbon dates available (Figure 8) indicate that this population of pine is broadly synchronous and flourished briefly across the Highlands of Scotland from 3500 ^{14}C cal. yr BC to subsequent collapse about 2300 ^{14}C cal. yr BC.

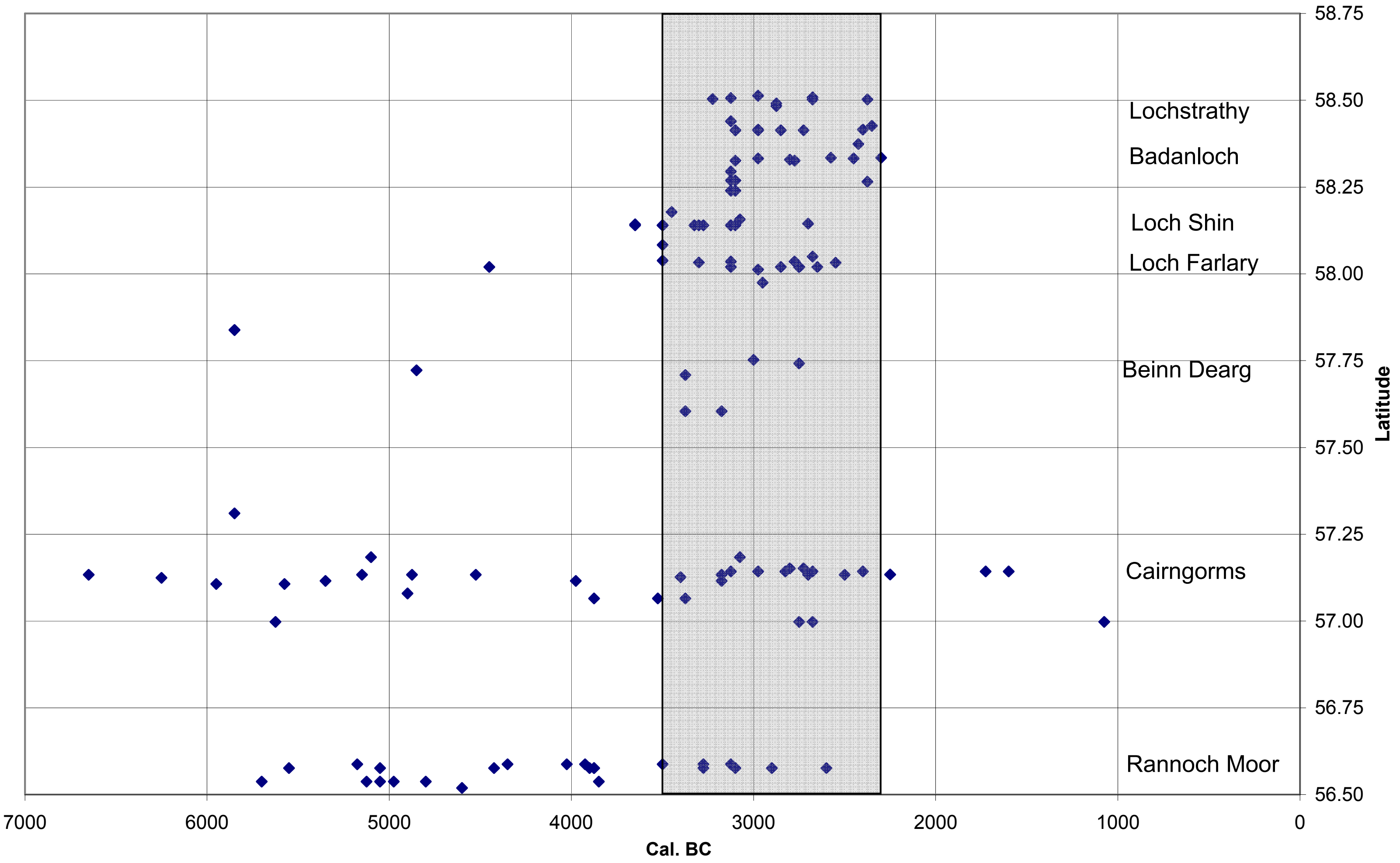


Figure 8: Radiocarbon dates over the range 7000-1000 ^{14}C cal. yr BC for Scots pine at different latitudes in N. Scotland with some of the larger study areas identified (mid-points of 95.4% 2σ range plotted).
Grey zonation denotes period 3500-2300 ^{14}C cal. yr BC. See Appendix I for radiocarbon data and sources.

1.2.6 Changes in the elevation of pine

Steven & Carlisle (1959) report the highest find of modern Scots pine on Ben Macdhui at about 840 m and a natural tree line on Craig Fhiaclach at about 615 m, both these sites are located in the Cairngorms. The radiocarbon dates of stumps found in peat above the present tree line (Pears 1968, Kullman 1988) indicate fluctuations in the altitudinal limit of boreal forest in northern Europe over the last 10, 000 years. Kullman's data suggests that the tree line may have been 200m higher 8500 years ago when temperatures are believed to have been 2ºC warmer. There also appears to be a general decline in the upper limit of pine macrofossils westwards and northwards from the Cairngorms.

Records of Scots pine macrofossils at 880 m in the eastern Cairngorms (NGR NJ 071 006) indicate an elevated tree line at 3000 ^{14}C cal. yr BC, their absence between 1900-700 ^{14}C cal. yr BC perhaps indicates that the tree line fluctuated during this period before its final decline (Huntley *et al.* 1997). If this elevation of tree line is a reflection of temperature, than the 250 m increase implies a mean temperature increase of about 1.5-2.0°C, according to the prevailing lapse rate. Huntley, also identified subfossil Scots pine at 305 m, at latitude 58º20' north on Ben Loyal (one of the northernmost mountains in far northern Scotland) that can be assumed to be part of the expansion at about 3400 ^{14}C cal. yr BC and suggests a minimum tree line for this area during the period. The maximum altitude of subfossil Scots pine in the south Pennines at this time (between 3400-2000 ^{14}C cal. yr BC) is just over 500 m (Tallis and Switsur 1983).

1.2.7 The pine decline 2000 ^{14}C cal. yr BC

The mid-Holocene decline of Scots pine about 2000 ^{14}C cal. yr BC in northern Scotland, England and western Ireland is well documented (Bridge *et al.* 1990, Gear and Huntley 1991, Pilcher *et al.* 1995, Lageard *et al.* 1999, Mighall *et al.* 2004). The rapidity and wide spatial extent of the decline has invariably been assumed to indicate a response to climatic change (Dubois and Ferguson 1985, Bridge *et al.* 1990, Gear and Huntley 1991, Anderson *et al.* 1998), although the influence of anthropogenic activity has not been disproved (Birks 1975, Bennett 1995). The mortality of trees could be the result of a number of mechanisms including damage by mammals, insects, fungal pathogens, windthrow, fire, and ice (McVean 1963a, Birks 1975, Blackford *et al.* 1992). While the main pine decline in NW Scotland is expected to have been, in part, a response to increased moisture, clear evidence is still required. McNally & Doyle (1984) and Bridge (1990) show that despite a general story of pine extinction in northern Scotland, pockets can survive long after this decline.

1.3 The dendrochronology of Scots pine

The term dendrochronology has been broadly defined to include all tree-ring studies where the annual growth has been assigned to or is assumed to be associated with specific calendar years. Inter-annual fluctuations of climate are transferred to large-scale variations in ring-width which can allow tree-rings from sites hundreds of kilometres apart to be cross-matched (Fritts 1976). Dendrochronology may be divided into a number of subfields, the term dendroclimatology refers to dendrochronological investigations of past and present climates (Fritts 1976), while dendroecology refers to dendrochronological investigations of ecological processes.

A considerable body of published work exists on the dendrochronology of Scots pine in Europe, but its study in the British Isles is limited. Dendrochronological and dendroclimatological methods are useful tools for revealing the dominant factors influencing radial tree-growth (Fritts 1976, Briffa and Cook 1990). A prerequisite for dendroclimatological studies, however, is a high sensitivity of tree-growth to climate. Control of annual growth by environmental factors, particularly climate, is strong and clearly discernable in areas where trees grow in marginal environments (Schweingruber *et al.* 1979). Of particular relevance to this study, there are numerous examples of successful dendroclimatological studies on pine at the upper tree limit which is primarily controlled by summer temperature during a short growing season (for a review see Schweingruber, (1996)).

Measurements of the modern growth of Scots pine growing under extreme conditions in the northern timberline in Finland have shown good correlation between ring-width and mainly July temperature (Briffa *et al.* 1990, Lindholm 1996). These results are consistent with the classic view that the tree line is determined by summer temperature, being roughly coincident with the 10 °C isotherm (Brockmann-Jerosch 1913). Precipitation and summer temperatures are expected to be responsible for the average tree-ring signal that permits cross-matching of the trees between most sites.

1.3.1 Dendroclimatology in Scotland

In cool humid regions, where precipitation is over 1000 mm yr^{-1}, it is probable that rainfall does not limit the growth of Scots pine on normally drained sites (Tranquillini 1979). Western Scotland receives between 2000-2800 mm and eastern Scotland 900-1300 mm of precipitation yearly. In western Scotland, the maritime climate with high temperatures from June to October promotes a relatively long growth period (4-5 months). In higher, cooler regions of the highlands, development of the annual ring begins approximately one month later and ends earlier, in September. Tranquillini’s studies found a short (2-3 month) growth period in pine in the subalpine region of the Alps, where only the high temperatures of August and September permitted development of the latewood cell wall. In a warm site, cell division is likely to begin in March; thus the climate for this month can have a major effect on ring width.

A study on Scots pine in a Mediterranean climate in Catalonia, Spain (near to the southern limit of the species), identified ring-widths as positively related to precipitation at the beginning of the growing season in March and June of the current year of growth, and in September of the prior year (Gutiérrez 1989). This research also found that during the winter, ring-widths are positively correlated with mean monthly temperatures mainly in December. The result suggests major factors controlling the southern distribution may not only be water stress in summer, but also the amount of precipitation at the beginning of the growing season and in the autumn, even in mild winters.

Schove and Frewer (1961) found no correlation between climate data and the growth pattern of Scots pine growing at Speyside in Scotland. Correlation between ring width deviations, rainfall during May of the same year, annual temperature for the same year, and rainfall during May plus June of the previous year were, however, later established from Scots pine at Alltcailleach Forest (Miller and Cooper 1976). Ring width deviations and the three significant climatic parameters were then subjected to spectral analysis and 4.44, 11.9, 23 and 42 year significant periodicities identified in all data. The oscillations were only identified in the climate data from Balmoral and Braemar (both in the rain shadow of the Grampian Mountains), which led the authors to suggest that they could reflect variations in the strength of the westerlies. Close similarity between ring width patterns found at both Alltcailleach and patterns published for pine growing in the rain shadow of the Norwegian coastal mountains was thought to offer support to the conclusion.

Another early dendroclimatic study reconstructed July-August surface air temperature for Edinburgh, Scotland for the period AD 1721-1975, used maximum latewood density and ring-width data from nine pine tree sites in Northern Scotland (Hughes *et al.* 1984); nine sites further described by Hughes (1987), all on relatively impoverished soils, with a varied aspect and slope. The cross-dating of the ring width sequences between sites was good, comparable to many between oak chronologies over similar distances (Pilcher and Baillie 1980).

Hughes (1984) found calibration for June remarkable poor. This is consistent with the model for environmental control of maximum latewood density in conifers in cool, humid regions discussed by Schweingruber *et al.* (1979), in which no secondary cell development occurs in a period in May and or/June. Possibly because maximum latewood density is dependent on one particular aspect of the seasonal climate, the year-to-year variations in all five chronologies of density data for the Scottish Highlands were similar despite a wide range of site, ecological and stand characteristics. Although tree-ring width is believed to be related, through various mechanisms, to climate conditions over much of the year (Fritts 1976), maximum latewood density has been found to be mostly a function of late summer temperature at high latitude and high altitude sites (Conkey 1982). This was confirmed by early dendroclimatic analysis of tree-ring width and density data from Scottish pine, identifing the strongest relationships with July and August (Hughes *et al.* 1984).

Work in Scotland by Hughes (1987) found unambiguous correlations between tree-ring densities and summer temperature, which clearly over-ride differences between sites, even in the mountainous region of the Scottish Highlands. Response functions were identified as slightly less effective predictors of ring widths, but that performance was better at most of the higher altitude eastern sites than in the west. Probably due to difference in sites, little consistency in the response functions for ring width was identified. Hughes nevertheless, found all sites to have significant negative correlation with the prior August's temperature and sites in the Cairngorm region significantly positive correlation with spring temperature. Prior growth was also found to be an important predictor in all the ring width chronologies except Glen Affric.

Climate response functions calculated using the method of Fritts *et al.* (1971), identified climate to be a less effective predictor of ring width site chronologies than maximum latewood density, although its performance was found to be better at most of the higher altitude eastern sites than the west. Prior growth was again identified as generally an important predictor in all the ring width chronologies except Glen Affric. The production of earlywood plays an important part in the determination of ring width. In contrast to maximum latewood density, this is influenced not only by current conditions but also by the storage of carbohydrates in parenchyma cells during the preceding late summer. Thus it is expected that earlywood, and hence ring width, will display a higher serial correlation because of its relationship to events in the previous years (Hughes 1987).

Analysis by Grace and Norton (1990) of seven sites along an altitudinal gradient at Creag Fhiaclach located on the Western flanks of the Cairngorms (648 m), found temperature to be more important than rainfall in influencing growth. Both late-winter (January - February) and summer (July - August) temperatures were significantly and positively correlated with ring-width. Grace and Norton suggested winter browning or frost drought as the mechanism of the winter temperature correlation. Also "Krummholz" trees at the tree line were found to grow more, and their growth was less strongly correlated with climatic factors, than trees at lower elevations.

Few dendroclimatological investigations have been made on trees growing on peat surfaces and there are no previous studies in Scotland or the UK. Linderholm (1999) cites Lundh (1925) that on drained peatlands in Sweden no correlation was found between annual Scots pine growth and either temperature or precipitation. In Estonia (Läänelaid 1982) and central Russia (Vaganov and Kachaev 1992) only weak relationships between the ring width of pine growing on raised bog and climate was found (both references cited in Linderholm {Linderholm 1999}). Though more recent analysis at two sites in Sweden has demonstrated bog pine to have a positive relationship with precipitation in May through to August (Linderholm 2001), and a positive relationship with temperature both in July and August as well as precipitation in January (Linderholm 1999)

1.3.2 X-ray microdensitometry

In comparison to ring widths, density measurements are more useful in the identification of partial rings, but problematic when it comes to narrow rings. The cross-matching is also generally stronger (Hughes 1987). However, radial growth chronologies of Scots pine in Siberia were found to be more sensitive to local weather influence than density chronologies (Savva *et al.* 2001). Dendroclimatic studies by Schweingruber (1979) using X-ray densitometry readings on tree-rings indicate that the cambial activity and growth rate of cell walls in latewood of all conifer species from cool humid regions is limited mainly by summer temperatures. Since earlywood production is principally controlled by prior growth and microsite conditions, earlywood ring width has no direct relationship to climate. An apparent negative influence of high precipitation on maximum density was thought to be artificial, because precipitation and temperature are related (Tranquillini 1979).

Its increased cost aside, the method of X-ray microdensitometry required to produce maximum latewood density has a number of important limitations, which restrict its application in Scotland. The method requires a relatively regular wood structure and is not suited to the analysis of extremely narrow rings (Hughes 1987). Density measurement of subfossil wood is also thought to suffer difficulties from post-mortem changes (Swain 1987). In spite of Hughes' (1987) conclusion that there is little consistency in the response function for ring width, except that all had a significant negative element for the prior Augusts temperature, most subsequent research has nevertheless relied on the analysis of ring widths.

1.3.3 Changing Signals

To predict change and allow management it is important to know the common physiological response/ecological response of Scots pine to environmental factors such as:

temperature, rainfall, wind, site hydrology, lake levels and pine ecology. Boreal forests are sensitive to climate change and various joint efforts are being undertaken to predict the effects of an anticipated near-future global warming on trees growing at or near tree line (Hicks *et al.* 2000, McCarroll *et al.* 2003). However, dendroclimatic reconstructions, like many other palaeoclimatic techniques, are based on uniformitarian assumptions and several accounts present evidence of a reduction of tree growth sensitivity to climate in the Northern Hemisphere (Jacoby and D'Arrigo 1995, Briffa *et al.* 1998c, Linderholm *et al.* 2002). Wilson (2004) reports changes in signal relating to atmospheric loading effects, Huang (2007) reviews evidence for the response of forest trees to increased atmospheric CO_2. A variety of causes have been proposed, including increased moisture sensitivity once summer temperatures pass a critical threshold (D'Arrigo *et al.* 2004), possible ozone-related effects (Briffa *et al.* 2004), or even chronology development techniques (Wilmking *et al.* 2005). The mechanism behind this apparent loss of climate sensitivity has yet to be confirmed, the evidence suggests that temperature increase, especially in the last two to three decades, has caused trees to respond differently to climate than during earlier decades of the twentieth century. While not universal, these effects need careful scrutiny and further study to resolve this potentially critical issue (Luckman 2007).

1.3.4 Wind and North Atlantic Oscillation

Metzger (1893) first proposed wind as the most significant factor affecting the growth of trees. Quine (2003) considers wind as the principal agent in the disturbance of British forests at present. The effects of wind on tree growth can be clearly seen in the uplands of Scotland (Figure 9 and Figure 10), where it exerts serious detrimental effects on commercial forestry (Miller 1985), yet this factor is rarely considered or examined in palaeoclimatic or dendroclimatic studies.

Figure 9: Tree growth restricted to a sheltered gully near Tongue on North coast of Scotland. Photograph by: A. K. Moir, 2001.

Figure 10: A windthrown pine near Achanlt. Photograph by: A. K. Moir, 2004.

Allen (1992) defines four broad classes of wind damage: windprune, windsnap, windtilt and windthrow. Windsnap, windtilt and windthrow are normally terminally catastrophic events for trees which result from occasional extreme high wind events. However, in areas with extremely strong prevailing winds, trees receive the force of the wind predominantly from one direction. Over time, windprune results in a distorted asymmetrical lower form to trees and a streamlined profile to canopies (Allen 1992). Damage to buds, shoots and leaves on the windward side occurs by a combination of rubbing (Rushton and Toner 1989) and wind-borne particles (such as rain, hail and snow). Wind augmented with salt-spray (Moss 1940) can also account for windprune (Figure 11 and Figure 12), up to 5 km inland, but the force of wind alone is also sufficient to account for the effect inland (Doutt

1941). High winds can even remove whole branches (Craighead and Gilbert.V.C. 1962, Dittus 1985), thus causing the foliage to be actively discouraged from growing windward, resulting in it mainly pointing downwind and the trunk normally leaning away from the wind. This makes the tree much more streamlined, reducing the wind forces to which it is subjected. In the most exposed areas, the wind tends to kill off the leading shoot at the top of the tree so that trees develop the prostrate "Krummholz" form common at tree lines.

Wind can also lead to strengthening of the cambial tissues in the trunk and the growth of larger roots to leeward. The mechanical properties of wood in trees with a windswept form may change due to structural and geometrical modifications in the new xylem cells produced (Telewski 1989). Root architecture and anchorage can also be affected {Mergen 1984; Stokes 1995; Nicoll 1996; Mickovski 2003}. The growth of pine at latitudes further north in Norway (Figure 1), indicate that pine should be able to grow further north in Scotland, and it is suggested that wind is the primary factor limiting its spread north. Topography can dramatically reduce precipitation particularly in valleys and also increase drying through wind effects.

Figure 11: An example of flagging, where wind blast (here exacerbated by salt spray) limits the trees height and creates a streamlined crown. Tree located at Durness on the north coast of Scotland. Photograph by: A. K. Moir, 2001.

Figure 12: Possible fatal effect of wind blast exacerbated by salt spray on a tree at Durness on the north coast of Scotland. Photograph by: A. K. Moir, 2001.

The most important variation in atmospheric mass, energy and momentum in the North Atlantic-European sector in all seasons is associated with the North Atlantic Oscillation (NAO) (Walker 1924, Lamb and Peppler 1987, Kushnir and Wallace 1989) . Its variability is an important source of regional climate anomalies at seasonal to decadal timescales (Van Loon and Rogers 1978, Rogers 1984, Hurrell 1995, Hurrell and Van Loon 1997). In Scotland, a significant proportion of the interannual precipitation and temperature variability is attributed to the dynamics of NAO, which is a measure of the pressure difference between the Azores and Iceland and hence affects westerly winds blowing across the North Atlantic (see section 2.3.5). Some studies on living conifers have indicated that ring widths tended to be wider to the lee of the prevailing wind (Bannan and Bindra 1970, Hamilton 2002). The author has read unattributed comment that along the exposed west coast of Britain, trees have narrow tree rings towards the south-west, (facing the prevailing wind), and wider tree rings on the north-east lee side. A recent study in Northern Fennoscandia found Scots pine growth to be positively related to early winter

North Atlantic Oscillation indices (a proxy indicator of wind), previous to the growth season and indices of late spring (Macias *et al.* 2004).

Linderholm (2001) compared modern tree ring-width chronologies from wet and dry sites at 526 m in the west central mountains of Sweden, where the pine tree-limit is at about 700 m altitude. The tree ring chronologies are compared against climate data from a site with an average annual temperature of about 13ºC and rainfall of about 635 mm. The study identifies that temperature during the growing season (May-August) shows the strongest influence on tree growth, and that the strength of the climate-tree-growth relationship is weaker at the wet site. Both site chronologies exhibited common spectral peaks, pointing to a maritime influence on decadal scales, which led Linderholm to conclude that Scots pine in that environment may be regarded as proxies of North Atlantic Ocean coupled climate variability. Later, Linderholm (2003), from the investigation of nine sites of pine across Norway, Sweden and Finland, showed pine growth to have a weaker relationship with NAO indices than temperature and precipitation. During summer, pine responded to NAO only in western Fennoscandia, while in winter it responded across both the west and east of this region.

Skewed ring growth in subfossil pine has been commonly observed by the author in both Modern and Holocene Scots pine in the north of Scotland. This indicates a direct directional influence on ring width growth and a potentially important chronologically precise proxy indicator for palaeowind that had not previously been investigated.

1.3.5 Holocene pine

Dendroclimatology offers great potential in climatic investigations of the Holocene period (as opposed to the Late glacial) due to the greater preservation of subfossil material from this period (Friedrich *et al.* 2001). A particular advantage of Scotland is that the Scots pine samples are *in situ* and are therefore in the context of a pollen record. The majority of long subfossil pine chronologies of most of Central Europe are developed from *ex situ* samples, many from river gravels (in Friedrich *et al.* 1999). Northern Scotland therefore offers a comparatively rare, wide source area of sites for dendrochronological investigation of the Holocene period and potentially provides a suite of palaeoecological information of precise dates. Furthermore, tree-ring series from near the timberline are exceptionally valuable, both for climatic reconstruction and investigations of the consequences of climatic change to ecosystems (Tessier *et al.* 1997). The potential of subfossil pine in Northern Scotland to identify and quantify climatic changes between about 3500-2500 ^{14}C cal. yr BC is expected to be good, due to the wide geographical extent of potential sites of preservation (i.e. bogs & mires) combined with their location beyond the current timberline.

1.3.6 Holocene subfossil pine chronologies

Unfortunately, unlike for oak, which exists back to 5518 BC (Pilcher *et al.* 1984), there is currently no continuous master pine chronology for the British Isles. The work of Smith and Pilcher (1973) and McNally and Doyle (1984, McNally and Doyle 1984) on subfossil pines in Ireland are early examples of tree ring research on Scots pine in the British Isles which used rigorous cross-dating on ring widths. Chronology construction has been most successful with trees from raised bogs, particularly where there is a predominance of trunks rather than stumps (Pilcher *et al.* 1995). Samples measured in early studies from a number of other prehistoric pine sites proved of insufficient length to enable cross-matching (Ward *et al.* 1987). Interspecies cross-matching with oak (*Quercus*) enabled the first successful dating of pine at Garry Bog in Northern Ireland, where Holocene populations of pine and oak coexisted (Brown 1991, Brown and Baillie 1992). Cross-matching of a 477-year pine chronology from the Thorne Moors, Humberhead Levels with oak chronologies from England together with long distance cross-matching to the Garry Bog pine chronology provided the first absolutely dated pine chronology from England (Boswijk & Whitehouse 2002). A *t*-value of 10.01 between Thorne Moors and pine trunks from White Moss, Cheshire provided the first successful cross-matching between pine chronologies from different raised mire sites in England (Chambers *et al.* 1997b).

In Scotland, there have been few dendrochronological studies on subfossil pine since the failure to cross-match 200 samples of subfossil Scots pine at Rannoch Moor (Ward *et al.* 1987, Bridge *et al.* 1990). Difficulties both at Rannoch Moor and later at Lochstrathy (Gear 1989, Gear and Huntley 1991) are considered to have been caused mainly by two characteristics of the sites: the lack of a clear synchronous horizon of pine and the generally young age of the trees which provided short tree-ring series. Analysis by Daniell (1997) found that few of the Lochstrathy samples (many with less than 50 rings) could be cross-matched and in the absence of replicated matches no mean chronology for this site was produced in his study. Nevertheless, subsequent research by Daniell (1992, 1997) and the author (1994, 1996) identify sites of apparent synchronous horizons of pine with sufficient rings to establish cross-matching. While from the sites known at present, subfossil pine preserved in Scottish mires are unlikely to establish the long (> 1000 yr) chronologies developed in Ireland and Western Europe, numerous > 250 yr-long pine chronologies have been created. Long-distance cross-matching of shorter chronologies to provide calendar dates is well established (McNally and Doyle 1984, Lageard *et al.* 1999). Daniell (1997) uses just two Irish chronologies from Sharvogues & Garry Bog (Brown 1991) to establish the first tentative calendar dates for Scots pine in Scotland. An increasing number of subfossil pine chronologies from northern Scotland, combined with the development of long chronologies in the rest of Europe (now covering the full length of the Holocene), increases the probability of calendar dating discrete chronologies and establishing calendar dates for climatic events.

1.4 Aims & Objectives

Despite the widespread analysis of Scots pine from both Modern & Holocene periods, surprisingly little is known about the ecology of Scots pine where it grew and became preserved in the peatlands of oceanic areas such as north-west Scotland. Dendroclimatological studies on modern Scots pine in Scotland have previously been limited to those growing on a mineral substrate. The potential to develop calendar-dated tree-ring chronologies to examine past climatic change from a broadly synchronous regional horizon of subfossil pine in the peatlands of northern Scotland has been largely ignored. The principal aims of this research are:

1. To compare Modern Scots pine growing on mineral and peat substrates to establish the ecological and climatic relationships of subfossil Scots pine found in Holocene peat of northern Scotland.

2. To understand why subfossil Scots pine is widely preserved well beyond its present-day tree line in the peatlands of northern Scotland and highlight its significance in the precise timing of past climatic change.

3. To investigate the possible relationship of skewed ring growth with wind in modern Scots pine and explore whether subfossil pine might also provide a proxy indicator of palaeowind.

2 METHODS

The counties of Scotland refer to those prior to the local government reorganisation in 1975. The locations of samples were recorded to eight figures of the Ordinance survey national grid reference (e.g., TN 1234 1234) with a hand held Magellan GPS 310 device, stated to be accurate to within about 15 m. Trees within 10 m of each other were usually recorded with the same 10 m co-ordinate, but were plotted in their relative positions on the location diagram for clarity. National grid coordinates were converted to ETRS98 geodetic, decimal degree latitude & longitude using GRIDQUEST software. Location maps were produced via Digimap from EDINA (the Joint Information Systems Committee national academic data centre based at the University of Edinburgh, http://digimap.edina.ac.uk).

Altitude was read to the nearest 10 m from 1:50000 OS maps and described in accordance with Birise (1971): Lowland (0-150 m), Foothill (150-325 m), Upland (325-675 m). Where appropriate, mire type was categorised in accordance with Lindsay (1995). Throughout this study, the terms the north-west (NW) area or south-east (SE) area of northern Scotland are used as a simple division of the sites sampled. The divide of these areas can be visualised as along the Great Glen Fault (Figure 3), although Monadh Mor and Pitmaduthy Moss, which are categorised as from the SE, are some 10 km NW of this divide.

2.1 Dendrochronological analysis

The general methodology of tree-ring dating is that described in English Heritage guidelines (Hillam 1998). Details of the precise methods employed for this research are described below. Tree-ring analysis and graphics were achieved via a dendrochronological programme suite called DENDRO developed by Ian Tyers of Sheffield University (Tyers 1999). Dates are based on the Gregorian calendar and there is no year zero between BC and present calendar dates.

2.1.1 Sample size

Sample size is particularly important in dendrochronology for two reasons. Firstly the Principle of Replication (Fritts 1976) states that by sampling several radii per tree and several trees per site, then averaging the results, the "signal to noise ratio" can be maximized. In this instance, the "signal" refers to ring width variation due to climate, assuming that pollution and other exogenous disturbances do not significantly affect growth. The "noise" component refers to variation due to non-climatic factors, such as aspect, hydrology, competition, and crown damage (Fritts 1971). As well as reducing "noise", a large sample increases the likelihood of cross-matching by being able to identify ring anomalies in individual samples. Modern dendrochronological studies have also shown that a wide source area of sites (both in geographical and ecological terms) assists the long-distance cross-matching required at present to provide calendar dates.

What constitutes an adequate sample depends on the characteristics of the growth at a site. Where the climatic signal is weak, increasing the sample size helps to reduce the non-climatic noise. Similarly, if the site conditions are extremely limiting to growth, a large sample is necessary to ensure accurate cross-matching. As a general guide, Fritts (1976) suggests at least two radii from 20-30 trees. Tate (1997), however, notes that many studies use far fewer trees. Earlier workers generally established modern Scots pine chronologies using samples from about 12 trees and therefore similar levels of replication were aimed for in this study.

2.1.2 Site selection criteria

Tree-rings are one of the most important proxy data sources for reconstructing past climate variability. However, to identify and understand climate variability, wide spatial and temporal coverage is required (Adams *et al.* 1999). Another major consideration of selecting sites was to attempt to extend the existing network of Scottish Holocene pine sites of Daniell (1992, 1997), in order to maximise potential cross-matches and to help refine interpretations on the rate and direction of pine spread across the region. Radiocarbon-dated pine north of the latitude of 58° in Scotland identify a broadly synchronous population, between about 3,500-2,300 ^{14}C cal. yr BC (Figure 8), therefore only locations above this latitude were explored. Fieldwork in the summer of 2001 explored for exposures of subfossil pine in Scotland. The highest occurrences were identified at:

- The edges of reservoir lochs (where changes in water levels had promoted peat erosion)
- Peat workings
- Roadside cuttings, drainage ditches
- Streams and rivers (where erosion had occurred into a peat bank)

Reservoir lochs and peat workings generally provided the most extensive exposures of Holocene pine, but each site was assessed for its dendrochronological potential. Groups of more than 10 pine stumps, containing at least 150 rings, traces of bark and *in situ* samples were the main considerations. Accessibility was also a factor in the identification and selection, which due to the means of transport tended to be within view of a road. While it was recognised that success in cross-matching is likely to be less when samples have less than 200 rings (Pilcher *et al.* 1995), Daniell (1997) established that Scottish sites with numerous shorter samples or individual long tree-ring series could cross-match. Samples were collected from some sites during their assessment. Where these contained sufficient rings they were often included to increase the depth and range of the study. Where more than one layer of subfossil pine was identified, the upper (most recent) horizon generally contained the most accessable samples and was targeted for sampling.

2.1.3 Sampling and preparation

Each site sampled during the course of this study was assigned a four letter code. Thus each tree and its measured ring sequence were identified by a four letter code followed by the sample number. The data from earlier studies are referred to by their original codes. The site code, sample number and direction of north were labelled directly onto each sample as it was sampled. Holocene pine which were sampled but subsequently found to contained less than 50 rings (this being the minimum number generally considered necessary for analysis (Hillam 1998)), were rejected from further analysis at this stage. Ring sequences with fewer than about 30 rings are definitely not unique and should not be used for dating purposes (Mills 1988), therefore where samples from living trees were recovered with bark sequences, down to a minimum of 35 rings were measured.

Most stumps preserved in peat were excavated down to the trunk/root collar interface to expose the best preserved areas. Sampling at the trunk/root collar was also considered desirable to help identify the year of germination and maximise the numbers of rings for analysis. The height of sampling above or below the trunk/root collar and location were recorded for each sample taken. Samples were initially sawn in the field using a "Champion" 38 cc 2-stroke petrol chainsaw with a 0.41 m cutting bar. Samples were then air dried for 6 months before being further cut and trimmed into approximately 0.10 m thick sections using a "Bosch" 1600 watt electric hand saw with a 0.35 m blade.

Live trees were sampled using hand driven increment corers, which normally leaves the tree unharmed. Extracted core samples were immediately glued and taped onto wooden laths on site, and then labelled with site code, sample number and orientation, before being left to air dry ready for subsequent analysis. Tree-rings were revealed by sanding with progressively finer grits, down to a 600 abrasive grit finish to produce a clean cross-sectional surface normally suitable for measuring. Further preparation, where required, was undertaken by hand.

2.1.4 Measuring

Tree-ring series are measures of tree radial growth from nearest pith towards bark, from the first to the last measurable ring, at annual resolution. Tree-ring sequences were measured under a x20 stereo microscope to an accuracy of 0.01 mm using a microcomputer based travelling stage. Two opposite radii per core tree were measured; Fritts (1976) suggests that more than this level of replication is usually not necessary in the case of modern trees.

Previous workers on subfossil pine have reported problems of missing rings (Pilcher *et al.* 1995) and therefore three radii were measured from most Holocene pine sections. Missing rings in Scots pine were most commonly identified in radii where ring width reduced to <0.2 mm yr^{-1} over 2 consecutive years or more, particularly where this low growth occurred in the first and end 50 years of tree growth. Where missing rings could not be resolved, through comparison of different radii, or by comparison to other sections, the unreliable sequences at the beginning or end of sections were ring counted and recorded. Dates of ring counted sections or where pith dates have been estimated are quoted as *c.* which indicates the actual year is likely to be within just a few years of the date. Each radii was measured twice, and the two sets of measurements generated e.g. ABEA01aa and ABEA01ab, were cross-matched and plotted visually to facilitate visual comparison as a means of identifying measuring errors. Where individual radii sequences matched satisfactorily they were averaged and the resulting mean sequence used in subsequent analysis, i.e., ABEA01a. On subfossil samples up to five radii were measured on problematic sections (i.e. ABEA01a, ABEA01b, ABEA01c, ABEA01d, and ABEA01e) and their cross-matching between each other and other samples fully assessed before establishing a mean sequence for the sample, which in this example would be called ABEA01.

2.1.5 Tree-ring reference data

To increase the scope of this study and assist dating, original ring width data from earlier Scots pine studies in Scotland were obtained where possible. The International Tree-Ring Data Bank currently contains data for *Pinus sylvestris* L. at 14 localities in the UK. These data are held in a format suitable for a tree-ring analysis program called ARSTAN. Raw tree-ring measurement data for all available sites were downloaded and converted into a format suitable for the program DENDRO (Tyers 1999). All raw tree-ring data were then processed using a common methodology wherever possible, to enable more direct comparisons.

A problem in transferring data from ARSTAN to DENDRO is that the latter software does not allow missing data, which are recorded in ARSTAN as a -9 value. Using a facility in ARSTAN for estimating missing values, it was possible to enter missing ring values for inclusion in DENDRO series. The majority of missing data were individual rings, but the ARSTAN was used to estimate the missing values for up to10 sequential missing years. Where sequences of more that 10 missing years occurred, the single series in ARSTAN was separated into two series (A and B) for use in DENDRO. Care should be taken in comparing the Creag Fhiaclach and Carrbridge sites as these data were truncated at 1880 and the earlier part of these tree-ring sequences has been lost (Pers. comm. Rob Wilson 2006, Edinburgh University).

The three chronologies from Badanloch, Loch Shin and Loch Vatachan had previously been reported as calendar dated to span 3155-2982 BC, 3441-3223 BC and 3404-3232 BC respectively (Daniell 1997). These were dated using a combination of ^{14}C dating and cross-matching against the Garry Bog pine 1 and Sharvogues chronologies (Brown 1991). In view of the problem of missing rings encountered during this study (discussed above) these reference chronologies were re-checked for narrow rings. Narrow rings occur near the ends of both the Loch Shin and Loch Vatchan chronologies; therefore the end 36 and 14 rings respectively were removed to establish two slightly shorter chronologies named SHIN-ED and VATCH-ED for use in this study. Narrow rings were also observed to occur near the beginning of the Badanloch chronology, and so the first 7 rings from this reference chronology were also removed, establishing a chronology named BADAN-ED.

2.1.6 Cross-matching

Three methods of cross-matching are used to ensure reliability: statistical tests, visual matching and replication. Cross-correlation algorithms were employed to search for the positions where tree-ring sequences correlate and therefore possibly match. Agreement is quantified parametrically using the product-movement correlation coefficient, which in turn is adjusted for the amount of overlap between chronologies and reported using the standard *t* statistic, derived from the original CROS73 algorithm (Baillie and Pilcher 1973). The Student's *t*-value expresses the degree of affinity of two time-series (Baillie and Pilcher 1973). To gain reliable results, a minimum of a 40 year overlap of cross-dated time-series should be reached (Pilcher 1990). A *t*-value of 3.5 for an overlap of 100 rings gives a 0.1% significance level, indicating that this value should occur by chance once in every 1000 miss-matches (Baillie 1982). Values of *t* in excess of 3.5 are quoted as significant and indicative of acceptable matching positions, although statistical testing of *Pinus* data by Pilcher (1995) suggests that *t*-values of 4 or greater can be regarded as an acceptable match. Due to the risk of high *t*-values being produced by chance, all indicated correlations were further checked to ensure that corroborative results were obtained at the same relative position against a range of tree-ring sequences. Visual comparisons of sequences were also employed to support or reject possible cross-matches. Although this visual check is a subjective assessment (Figure 13), the human eye is able to detect similarities between ring-width patterns and anomalies such as missing rings, that no objective statistical methods can (Hillam 1998).

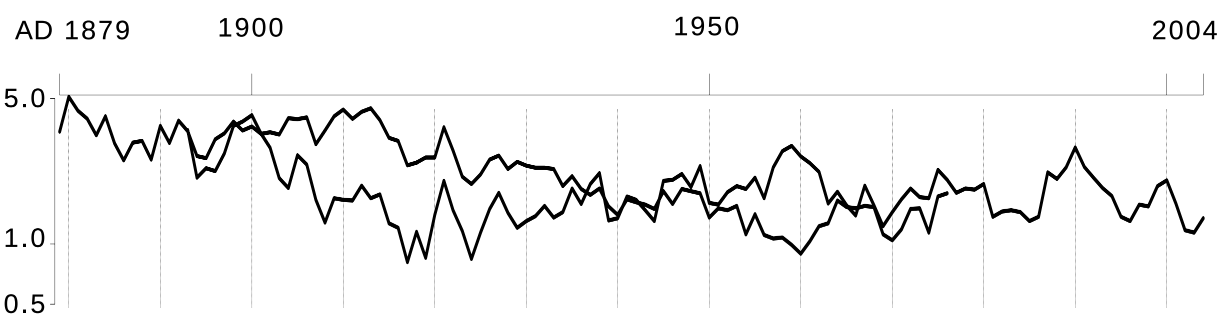


Figure 13: Plots of the tree-ring sequences ACHA-7 (upper) and PLOCKTON (lower) which cross-match together with a *t*-value of 6.9.
Ring width (mm) is plotted on a logarithmic scale on the y axis, using a common axis. Plockton chronology developed by Hughes (1987).

Schulman (1941) states the principle of cross-dating is the scientific "control" in tree-ring analysis, and that no one sequence of rings, no matter how carefully selected, can be trusted to give a faithful record unless it is supported by records from other trees over a considerable area. Replication of cross-matching is where ring sequence A matches B, it should also match C and the match should be similarly replicated with other samples. If A matches with B but not C, one of the results may be spurious, and all the tentative matches in the group should be rechecked. Not every pair of rings from a matching group will produce t-values over 3.5, but as a general rule it is useful as a good way of indicating where there may be problems of cross-matching (Hillam 1998).

Where radii were found to match, the sequences were averaged to produce a mean curve for each radii and then each tree. In some cases, re-measuring the complete radii did not achieve successful cross-matching. In these instances it was sometimes possible to match part of the radii into a mean sequence, leaving out the problem section that could not be matched. The inclusion of such incomplete radii helps to strengthen the site chronology by providing more replication, and to lengthen the time period covered by it (Tate 1997).

The process of cross-matching compares all tree-ring sequences from a single site or area against one another, and those found to cross-match satisfactorily together (confirmed with satisfactory visual matching) are combined to create average sequences (site means). Site mean sequences and remaining unmatched ring sequences are then tested against each other and a range of independently dated reference chronologies; *t*-values over 3.5, replicated against a wide range of sequences at the same position and satisfactory visual matching are similarly used to establish cross-matches or cross-dating with reference chronologies. Successful cross-matching in a region indicates the influence of an external growth factor on tree growth (Eckstein *et al.* 1981).

2.1.7 Removal of growth trend and physiological preconditioning

Series of tree-ring widths commonly contain a growth trend, due to the average ring-width generally slowly decreasing as trees grow older (Stokes and Smiley 1968). This is partly caused by the stem increasing in diameter and the annual growth becoming spread over a wider circumference, but also because food and growth regulators produced in the crown of the tree have to travel further to reach a given point as the tree increases height (Fritts 1976). In climatic studies, it is usual to statistically remove this age trend from each sample, otherwise a mean chronology will show areas of high and low growth which are not associated with climatic change, but with the varying age of the samples. This process is called standardisation. The process of standardisation of each tree-ring sequence also prevents over-representation of wide-ringed samples at the expense of narrow-ringed ones, in a mean chronology. This has been considered particularly important because slow growing narrow-ringed trees are often under more climatic stress and provide more climatic information than fast-growing, wide-ringed trees (Fritts 1976).

Standardisation is therefore performed to remove low-frequency variability in individual tree-ring series that is assumed to be unrelated to climate, such as tree aging, forest-stand development, and differences in the general growth rate or vitality of individual trees (Cook 1987). The process removes the age-trend by fitting a curve to each ring width series and then dividing each ring width by the corresponding value of the curve. The resulting values (known as "indices") are then averaged year-by-year among the trees of different age to produce a mean chronology that is independent of the age of the samples. Tree-ring indices have a defined mean of 1.0 and a relatively constant variance. Standardisation has the disadvantage that it does not distinguish between long-term trends due to ageing and those due to long term climate change. The process can therefore potentially remove important information from the chronology.

A great variety of techniques have been used to define the growth trend, e.g. (Fritts 1976, Warren 1980, Cook and Peters 1981, Briffa *et al.* 1983, Holmes *et al.* 1986). In practise, growth trend can in most cases be determined as being the low-frequency component of the observed radial growth. It can be as simple as a regressed straight line, which is often (although arguably incorrectly) used as an alternative for negative exponential function, or a greatly more flexible frequency-dependent filter. The precise function selected to fit the curve to the ring-widths has considerable influence on the value of the resulting indices, and problems can occur where parts may not fit a function. The differentiation between the low-frequency variability due to climate, tree ageing and growth disturbances can be ambiguous. Due to the great disparity of methods, the choice of standardisation bears significant influence on the indices obtained and ought to be carefully considered. The choice is based on the general behaviour of tree-rings due to the source environment, as well as on the signal property desired.

A clear separation of environmental and tree-specific components is almost impossible using standard smoothing methods described by Cook *et al.* (1990). The application of advanced standardizing methods such as the regional curve standardization (Briffa *et al.* 1996) requires uniform site conditions and are less suited for material originating from different kinds of mires and stands of varying forest density. For these reasons, a number of standardisation methods were applied in order that the effects of each method on the tree-ring chronologies might be assessed:

> **Detrending 1**: used a single detrending method of standardization, achieved by fitting a negative exponential curve, or regression line, to each series and then dividing the widths by the fitted curve. General positive growth trends are unlikely to be related to tree ageing and forest-stand development, and therefore only negative slope linear regressions were allowed. Short series (>50 years), and those displaying periods of extremely narrow rings tended to cause the growth curve to go negative, and in these instances a general exponential curve, or failing this a straight line was used. Both the negative exponential curve and general exponential curve however, have inadequacies as models for growth trend, tending to fit the highly variable, steeply descending juvenile portion of the ring-width trend better than the less variable, flatter portion often associated with maturity and old age. In some cases, the outer portion of a ring-width series may be systematically under fit or over fit for decades.
>
> **Detrending 2**: Holmes et al. (1986) showed that a stiff spline fit along by the 67%*n* criterion was not sufficiently flexible to track the sharp curvature of the juvenile portion of the growth trend, but was adequate for the later phases of growth trend. Cook (1985), reasoning that the sequential use of the negative exponential curve/linear regression, followed by the 67%*n* criterion (a method called double detrending) should correct the deficiencies of each individual method, and concluded from examination of the spectral properties, that this method worked well without removing too much low-frequency variance.
>
> **Detrending 3**: It has become apparent that many commonly used detrending methods eliminate low frequency fluctuations. Briffa *et al.* (1996) demonstrated this fact on a 1500-year chronology constructed from overlapping short segments from trees whose individual life spans were much less than 1500 years. All

fluctuations longer than 30 to 40 years were eliminated by using a 67% spline function. The raw value curves and the curve detrended by a “general age-effect curve” (regional curve standardisation) seem to retain the best centennial fluctuations. Luckman (1993) proposes the standardisation of each individual curve by a moving average 25-year filter, so that the resulting mean chronology includes the long term fluctuations. Negative exponential curve/linear regression, followed by the 20 year spline were used for this research in this method.

Detrending 1, 2 & 3 methods of standardisation were performed using ARSTAN software (Holmes *et al.* 1986). Although a tree-ring starts and ceases during the beginning and end of the growing season respectively, the growth in that year may also depend upon the growth of the previous year. Climatic factors in the previous years can modify the capacity of the tree to respond to climate in later years. This relationship is called physiological preconditioning (Fritts 1976), and can be expressed mathematically by the autoregressive-moving average models (ARMA) of Box & Jenkins (1970) in tree-ring analysis (Cook 1985). Tree-ring indices can be modelled and prewhitened as AR or ARMA processes to result in series containing no persistence, just an amplified signal (Cook 1985). The program ARSTAN was used to produce residual chronologies, computed by averaging residuals from autoregressive modelling of detrended measurement series. Residual chronologies were use for climate response analysis as they contain a strong common signal, with little persistence (Lindholm 1996). Two other chronogies were also created by the program ARSTAN, the "standard" version (no autoregressive modeling) and the "Arstan" version, where the pooled model of autoregression was reincorporated into the "residual" version (Holmes 1994). However, these chronology versions were not used.

2.1.8 The descriptive statistics of standardised chronologies

Several descriptive statistics are commonly calculated in dendrochronology to allow comparisons between different chronologies and to permit comparisons with other dendroclimatic data sets (Fritts 1976, Briffa and Jones 1990).

Mean sensitivity (MS), is a measure of the mean relative change between adjacent ring widths and standard deviation (SD) which measures the variability of the widths of adjacent growth rings, and allows the high-frequency variations to be assessed (Fritts 1976). A mean sensitivity over 0.20 would be described as high. A high standard deviation generally indicates that the tree-ring series is highly responsive to environmental factors.

First order autocorrelation, also called Lag-1 autocorrelation coefficient, or serial autocorrelation (R1), describes the influence of the previous growth on the growth of the current year (Fritts 1976). The R1 reflects how much low-frequency variance has been removed by standardization methods. Theoretically it ranges from 1 to 0, values of 0.25 for pine have been described as high (Eilmann *et al.* 2006). Studies on pine at dry sites show similar R1 values (Oberhuber 2001, Rigling *et al.* 2002). Fritts (1965) and Rigling (2002) showed that influence of prior growth is reduced at dry sites. The mean correlation among trees for the common overlap period among series is called RBar. The value theoretically ranges from 0 to 1, the higher the value the more out of phase variance has been removed.

The coefficient of skew and coefficient of kurtosis are included to assess any higher order effects on the probability distribution owing to the method of standardization. Kurtosis is a measure of the "peaked ness" of the probability distribution of a real-valued random variable. Higher kurtosis means more of the variance is due to infrequent extreme deviations, as opposed to frequent modestly-sized deviations. Kurtosis can range from -2 to +infinity. Skew is a measure of the asymmetry of the probability distribution of a real-valued random variable. Roughly speaking, a distribution has positive skew (right-skewed) if the right (higher value) tail is longer, and negative skew (left-skewed) if the left (lower value) tail is longer. Due to the different numbers of radii measured between core and section samples and the difference levels of sampling, within-tree correlations were not examined.

The signal to noise ratio (SNR) is an expression of the strength of the observed common signal among trees (Wigley *et al.* 1984). SNR is defined as: SNR = $N\,r/(1-r)$, where r is the average correlation between trees and N is the number of trees within a site chronology (standardised tree-ring indices). SNR values (invariably related to the section of the chronology composed of the maximum number of cores) are often quoted as a measure of chronology quality. The higher the SNR value the better, but this is a difficult quality to interpret because it has no upper bounds and its use for comparing chronologies is problematical. Also the SNR is best suited for measuring the strength of the observed high-frequency signal in the tree-ring indices, not the persistent, low-frequency signal which may be of interest in the study of climatic change. Thus, the maximum SNR criterion may be biased towards selecting a digital filter that removes an excessive amount of low-frequency variance during standardization.

The expressed population signal (EPS) is easier to interpret than the SNR (Briffa and Cook 1990). Uncommon variance (noise) cancels in direct proportion to the number of series averaged. EPS quantifies the degree to which a particular sample chronology portrays the hypothetically perfect chronology, which may in turn be regarded as the potential climate signal (Briffa 1984, Wigley *et al.* 1984). The value ranges from 0 to 1, with 1 being the best possible value (the hypothetically perfect chronology). However, a specific range of EPS values which constitute acceptable statistical quality cannot be given. Wigley *et al.* (1984) suggest a threshold of 0.85 as reasonable. The most important source of EPS variations is series replication, rising very quickly as the number of trees increases from 1 to 10, but progressively slower for more than 10. The fractional common variance between the reduced sample-size chronology and the fully replicated chronology is the sub sample signal strength (SSS).

2.2 Stand Dynamics

Climate signal, both in its spatial and temporal variability, depends on the ecological conditions prevailing in the forest stand, because the signal is recorded through the tree-site complex.

2.2.1 Growth trend sequences based on the biological age of trees

In general, trees progress through three phases of growth: formative, mature and senescent (White 1998). Formative increment growth, nourished by the increasing foliage, tends to increase each year until optimum crown size is reached, usually achieved in 40 to 100 years. During the mature phase (foliage, weather and all other factors being equal), the annual increment produced remains constant in terms of volume. However, as a tree's girth increases, the annual increment is spread over a larger area and hence ring-width progressively declines. Die back of the crown and branches occurs during senescence, the final phase, and causes further reduction in ring-width.

A method of enhancing age related growth trend is described by Mitchell (1967). The ring-width measurements of each sample are aligned with those of the other samples according to the biological age of the rings, not the chronological age. Once the biological age alignment is completed, the ring widths of all the samples are averaged together to produce an average biological growth trend sequence. The averaging process greatly attenuates the yearly fluctuations in ring width due to environmental factors because of the chronological misalignment of the tree-rings. Consequently, the underlying growth curve is emphasized in these growth trend sequences.

Cumulative plots of growth trend sequences then help show the changes in radial growth rate which are normally associated with age. Cumulative plots of growth trend sequences are started at year 15 to allow that the earliest growth of trees is not normally sampled by increment cores and allows direct comparison between section and core data. Although this has the effect that the X-axis (cumulative ring-width) starts at zero at age 15, one can consider this cumulative ring-width starting at normal core sample height (1.37 m), this method is also commonly used in forestry yield tables (James 1982) . Comparing growth trend sequences of similar age then allows a better visual comparison of growth rates. The growth rate of sequences at any age can be simply calculated by dividing the cumulative ring-width value by age.

2.2.2 The use of pith and bark in tree aging

Where core samples did not include the central ring (pith), or the rings were too narrow to be measured, the number of rings to the pith was estimated. Where ring curvature suggested that the sample had been cored to near pith, a transparent acetate sheet marked with concentric rings of uniform width was selected to match the inner-most ring widths and this aligned over the sample so that the curvature of its rings matched those of the samples inner-most rings. The number of missing rings was then counted and classed either as very near pith (within 5 rings), or fairly near pith (within 10 rings). This method assumes that the rings missing from the samples were circular and the same width as the innermost ones present in the core. Where the pith was identified to be over 10 rings but could not be measured in the case of narrow rings, the number of rings were approximately counted and recorded. Where there was no evidence of pith on a core sample, 15 years was generally used in the age calculation. However, where other author’s tree-ring data was available, and there was no information on pith, it was assumed that the samples were probably cored fairly near to the pith and 10 years was used in their age calculation.

The centre of tree date obtained by sampling at a height above the ground may not necessarily represent the absolute age of the tree or the year of germination (Telewski and Lynch 1991). The discrepancy between the pith date obtained from cores taken at normal breast height (approximately 1.37m above ground) and the germination date obtained at ground level is only likely to be significant with suppressed growth trees, which might grow for 100 years before attaining a height over 1m (Tucker *et al.* 1987). Scott (2000) identified a 20-25 year period from germination for trees to reach a height of 1.5m on a suitable site at Ballochbuie, a height that can be recorded by collection of increment cores.

Pine trees growing on peat often display stunted forms that suggest slow growth and which could increase the possible discrepancy between pith date and the germination date. Destructive sampling of 10 trees between 0.5 and 1.3 m tall growing on peat at Pitmaduthy Moss, Monadh Mor and Inshriach, identified that discs taken at the root collar had only 3 ± 1.4 (S.D.) more annual rings than increment cores sampled from between 0.2m and 0.3 metres height (Anderson and Harding 2002). Therefore, to reduce the discrepancy between pith data and age in this research, trees growing on peat were generally cored low to the ground, but leaving sufficient clearance to turn the core handle. To compensate for the discrepancy in tree age calculated from root collar and samples taken from higher up the tree, a standard addition of 5 years was added to cored samples.

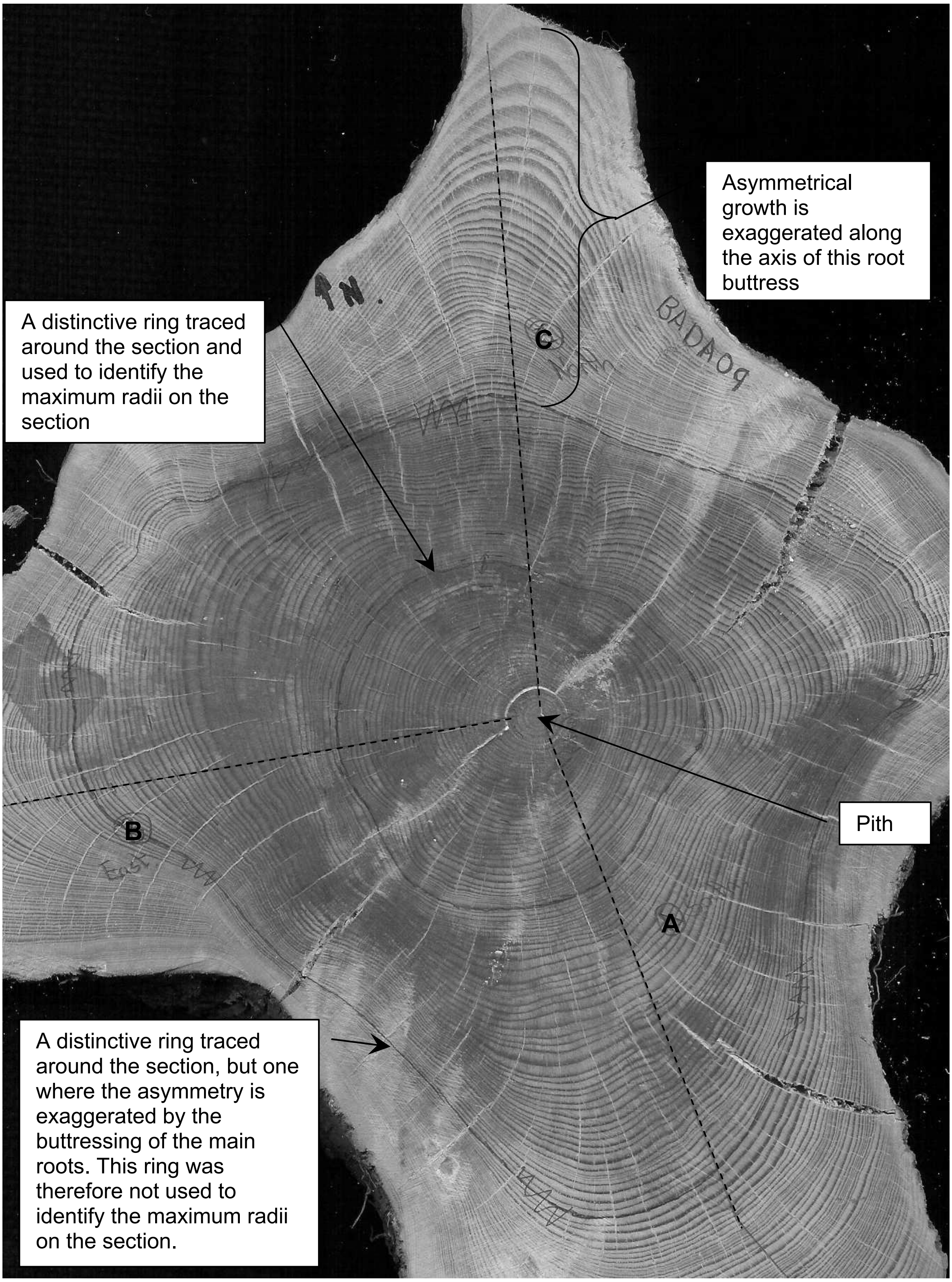
2.2.3 Patterns of regeneration

In 1930 at Glenmore in the Cairngorms and 1928 at Glen Garry, plots were deliberately disturbed and fenced from browsing, these found peaks in tree recruitment about 20 year and 17 years later, respectively (Edwards and Mason 2006). This lag between the removal of browsing and the subsequent regeneration is attributed to the slow growth of pine seedlings under these conditions. Subsequent to this germination lag, an extended "recruitment" phase appears to last about 30 years (Edwards and Mason 2006), therefore exponential decay seen in pith dates probably reflects a slow growth period and not a long period of gradual recruitment. A 20-30-year long pulse of successful pine regeneration is also identified in Scots pine growing on bogs in Sweden (Ågren and Zackrisson 1990). Age structure of Scots pine populations on undisturbed Swedish mires showed that pine recruitment patterns varied among mires with three types of dynamics (Ågren and Zackrisson 1990). A reverse-J shaped age class distribution indicated populations that had maintained a fairly constant rate of recruitment. Other unimodal age class distributions reflect a wave-like regeneration pattern, possibly resulting from interactions between different tree age and size classes. Where multimodal age class distributions were evident, the timing of the peaks of colonization coincide among sites, suggesting that these populations had experienced periods of abundant regeneration, probably due to climatic fluctuations. In this research a group of pith dates with a range of about 10 to 15 years was interpreted as probably germinated at the same time as the earliest pith date.

Where bark survives intact on a sample the precise age that a tree died may be calculated, but where bark is not recovered, only minimum tree age can be calculated and the tree may have died anytime after the last ring measured. The interpretation relies upon the nature of the final rings in the sequence. Based on the completeness of the final ring with bark, it is sometimes even possible to determine whether the tree was felled or died between spring, summer or winter, corresponding to approximately March to May, June to September and October to February, respectively. Where trees were felled or died in either spring or summer, the final ring is incomplete and therefore not measured, so allowance has to be made for the one-year discrepancy between the end of a measured sequence and the actual year of felling.

2.2.4 A possible relationship between radial growth and prevailing wind

To explore the possible relationship of palaeowind on Scots pine growth, where pine stumps were sampled *in situ*, details on stump height, root and stem orientation were recorded. The orientation of samples taken from trees was recorded and the length of the core measured from pith to bark or outermost ring. In the case of a section, north was marked on the top side of all sections. After sanding, an easily identifiable ring was selected, that could be traced around the entire section. This ring was not normally the outermost ring, but selected to be complete around the section. The ring was also selected before the clear influence of roots, which were observed to exaggerate the asymmetry of the pattern of rings (Figure 14). These factors resulted in the measurement for asymmetry usually being taken within the first 100 years of growth of the tree. The maximum radius was identified and together with its opposite minimum, measured from the pith to the traced ring along one of 16 directions numbered sequentially from 0 to 15: N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW, where N = north, E = east, S = south and W = west.



Asymmetrical growth is exaggerated along the axis of this root buttress

A distinctive ring traced around the section and used to identify the maximum radii on the section

Pith

A distinctive ring traced around the section, but one where the asymmetry is exaggerated by the buttressing of the main roots. This ring was therefore not used to identify the maximum radii on the section.

Figure 14: Section BADA09 showing the three radii measured (A, B and C) and exaggeration of asymmetry of tree-rings in the direction of root buttresses.
Scale 1:1, the underside of the section is shown, therefore the east radius is orientated to the right.
Photograph by: A. K. Moir, 2008.

To ensure that only coeval samples were compared, the direction of maximum/minimum radial growth was only examined on subfossil pine that cross-matched together into the regional master chronology. All modern tree samples were assumed to be of the same time period and therefore unmatched and unmeasured samples were also examined to increase the sample size; high winds could cause the failure of some unmatched samples to date, and therefore it was considered useful to include these samples. Where the difference between the maximum and opposing radii was less than 10%, it was considered that wind was probably not a significant factor in the orientation of maximum radial growth and therefore these samples were excluded from the mean direction calculated for each site.

The sites at Eilean Sùbhainn and Strathnaver C had trees thrown by wind to the west and north-west respectively; therefore these sites were sampled by north/south or east/west cores respectively to help identify the possible relationship with windthrow. Section samples have the advantage that the maximum direction of radial growth can be identified through comparing all the directions of growth. A clear limitation of core samples is that they can only compare the direction of maximum radial growth in the direction cored (i.e. generally east/west or north/south). Where all four compass points were represented by the cores taken from a site the mean direction was calculated. Where the results were ambiguous and maximum radial growth identified in two opposite directions, the percentage of samples in each direction as recorded, but considered insufficient to interpret the direction of prevailing wind.

2.2.5 Peat/root depth, orientation and stump height

A 2.5 m metal probe was used to record the depth of peat below the trunk/root interface of most samples (up to a maximum depth of 2.5 metres). Root depth and stump height were measured from the trunk/root collar interface. All measurements were recorded to the nearest centimetre.

A distinctive shape of root called “I” girder roots have long been recorded in the deep peats of Scotland and especially in the Caledonian forests (Anon 1964a). Figure 15 outlines the “I” girder cross-section form of a root that is typical of Scots pine found growing in deep peat. This shape is more than three times as resistant to bending in the vertical direction as a root with the same cross-sectional area but circular in section (Quine *et al.* 1995). Distinctive from normal root development in trees, “I” girder roots have shallow root growth in peat and the absence of a tap root (Figure 16 and Figure 17). Although Sitka spruce is shown in these two figures, pine is thought to respond similarly. The shallow rooting suggests anaerobic conditions at shallow depth and a water table never very far below the surface. According to Köstler *et al.* (1968), the depth of pine roots in mires is sharply controlled by the groundwater level. During sampling, where roots were exposed, depth and orientation of the largest root were recorded, as orientation of roots on stumps can reflect a tree’s physiological response to wind stress (Nicoll and Ray 1996).

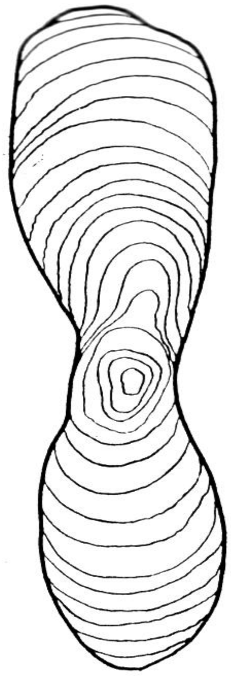


Figure 15: “I” girder cross-section of a root form typical of Scots pine found in deep peat. Source: Anon (1964a).

Figure 16: The deep development of Sitka spruce roots growing in 0.9 m of peat without a high water table. Photograph by: A. I Fraser.

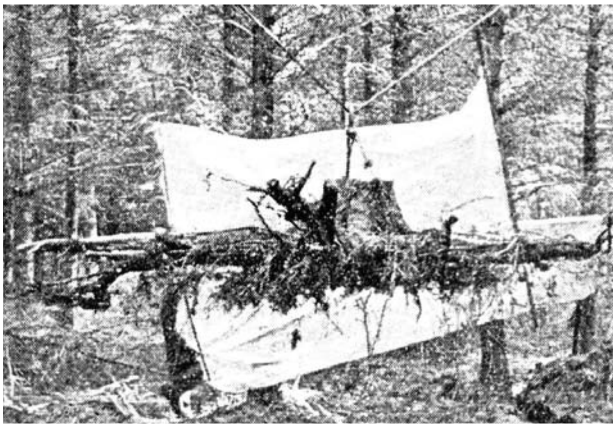


Figure 17: Shallow growth and "I" girder development Sitka spruce roots growing in 0.9 m of peat with a water table 0.3 m from surface. Photograph by: A. I Fraser

2.2.6 Scars

Death of part of the base of a tree by fire is seen in modern forests as tapering scars (Arno and Sneck 1977). Small scars caused by low/moderate intensity fires common in northern European boreal forests (Agee 1998), readily over heal and are more difficult to detect (Zackrisson 1980). Examining stumps in clear-cut stands (where scars are readily examined) or where complete cross-sections are sampled, can allow an accurate fire history record to be built. Where subfossil pine stumps are sampled using a chain-saw, the distinctive regrowth pattern of wood around the scar is often seen in the field (Lageard *et al.* 1999). Encapsulated firescars have been identified in cross-sections of felled modern pine trees (Lehtonen and Huttunen 1997) and subfossil pine (Chambers *et al.* 1997b). Surface charring could represent fire that scorched wood long after its death, and is not used (Leah *et al.* 1997). Careful use of increment cores can provide a satisfactory method for dating fire scars in living trees (Sheppard *et al.* 1988), although fire scars can be missed.

Scars in tree-rings may have a number of causes. Slope movements and avalanches are improbable on peatlands of northern Scotland, whereas wind damage, browsing and fire are assumed to be the likely cause of scars. Browsing control is considered essential for the successful establishment of modern pine (Miles and Kinnaird 1979). Scars caused by mammals may be evident in tree-rings after a tree has germinated. Hodge and Pepper (Hodge and Pepper 1998) state:

- Red, sika and fallow deer can gnaw bark (bark-stripping) from the trunk of young Scots pine (at the pole stage) all year.
- Fraying which results when male deer rub new antlers to remove "velvet" or to mark territories, normally between March and May.
- The height of the damage can help to reveal the species responsible.

To accurately date scar events, the scar must be at least partly encapsulated by later tree-rings. Where scars are located within dated wood, a scar event can be dated to the calendar year and sometimes the season of occurrence. Scars disturb the usual growth of tree-rings, therefore the more scars there are the more difficult the cross-matching and hence dating the sequences becomes.

Lageard *et al.* (2000) found significant wide rings indicating growth release immediately following the year of the fire and quantified the release in the two rings following fire by (F+1)-F and (F+2)-F. Where (F), (1) and (2) are the ring-widths (mm) in the year of the fire, in the year after and the second year after, respectively. The formula has two main problems. Early season fires are likely to bias the results to an increase in subsequent years and the weather in the year prior to a scar will also affect subsequent ring-width. The formula was therefore modified for use on scars to the sum of the two ring widths of the two rings before the scar, subtracted from the sum of ring width of the two rings after the scar and expressed as a percentage of change. It is not always clear whether a scar occurred late in a ring or very early in the subsequent ring. When in doubt the scar was interpreted as early in the subsequent year as the growth of this ring would be most effected. To examine possible longer term effects on growth rates, the mean ring-width of the period 20 years prior and subsequent to fire were compared and the difference recorded as a percentage of change. These methods are applied to both the sample with the scar and the mean chronology, to help determine whether a large area was affected.

2.3 Climatic Data

Monthly data from thirteen climate stations in north Scotland were transposed into a format suitable for dendroclimatological analysis (Table 2). The selection of these stations was based primarily on close proximity to sample sites, length of climatic record, and data accessibility. Nearest neighbouring rainfall series with the highest correlation were used to calculate missing values in the rainfall using software called ANCLIM (Stepanek 2006a) and PROCLIMDB (Stepanek 2006b). Rainfall correlations fall much faster with distance, and therefore the closest rainfall series were generally used. The rainfall record for Kinlochewe is short, only extending from 1953 to 2002, therefore data from Achnashellach (14km to the south) for the period 1941 to 1952, and from Portree (58 km to the west) 1861 to 1940 were used to extend the series. Achnashellach and Portree series correlate with the Kinlochewe with *r* values of 0.867 and 0.794 respectively.

Table 1: Climate station data used in this study

Station Name	**Latitude (dec. degrees)**	**Longitude (dec. degrees)**	**UK NGR**	**Elevation (AMSL, m)**	**Rainfall data**	**Temperature data**	**Sunshine data**
ACHNASHELLACH	57.49	-5.27	NH040491	67	1941-1983		
BRAEMAR	57.00	-3.40	NO15059074	339	1857-2004	1866-2004	1930-2003
CASSLEY	58.17	-4.73	NC396232	99	1961-2004		
EDINBURGH, BLACKFORD HILL	55.92	-3.19	NT258706	134	1785-1993		
FORTROSE	57.58	-4.08	NH75725634	5	1959-1994		
INVERNESS	57.50	-4.20	NH68264766	4	1841-1994	1959-2005	1959-2005
KINLOCHEWE	57.61	-5.31	NH 025629	25	1953-2002	1953-2003	1957-1999
LAIRG + LAIRG DAM	58.02	-4.41	NC579058	91	1961-2000		
POOLEWE	57.77	-5.60	NG 861818	6	1961-1993		
PORTREE	57.40	-6.20	NG47784219	20	1861-1984		
STORNOWAY (AIRPORT)	58.22	-6.32	NB46413382	15	1874-2004	1866-2004	1929-2003
TIREE	56.50	-6.90	NL98584497	9	1931-2004	1931-2004	1928-2004
WICK	58.45	-3.08	ND37065180	36	1850-2000		

Temperature can be generalized to wider areas, since its spatial correlation decreases with distance very slowly. Monthly temperature series for the Scottish mainland (SMT) and the northern and north-western Scottish Isles (SIT) have recently been developed back to 1800 and 1827, respectively (Jones and Lister 2004), and in view of the length, homogeneity and availability of these data, it was opted to use the SMT and SIT monthly temperature data in analysis. To help understand the possible relationships between climate and Scots pine growth in Scotland, it was considered useful to generally describe the current climate. Under the subsequent subheadings (unless otherwise referenced in this section), the information and statistics are drawn from those produced by the Meteorological Office (www.metoffice.gov.uk). Most statistics were produced using climate station data covering a 30 year period 1971 – 2000.

2.3.1 Rainfall

Annual precipitation in Scotland ranges from between 2000-2800 mm in the west to 900-1300 mm in the east. Northern Scotland is greatly influenced by the presence of the Atlantic Ocean and Gulf Stream to the west, and which interact with the North-west Highlands and Grampian Mountain ranges. There is a greater influence of maritime air in the western half of the Scotland, which means that it receives considerably more rainfall than the east. The North-west Highlands and the Grampian Mountains forces the prevailing southwest air from the Atlantic to rise, greatly amplifying this broad geographical gradient. The western mountains of Sutherland produce extremely high orographic rainfall (up to 2500 mm) and then a marked rain shadow effect eastwards, so that precipitation rapidly declines to 1200 mm in central Sutherland and is only 700 mm at the north-east tip of Caithness (Figure 19).

2.3.2 Temperature

The mean annual air temperature at low altitude ranges from about 7 °C on Shetland in the far north, to 9 °C on the west coast in the south (Figure 20). Normally temperature decreases by approximately 0.6 °C for each 100 m rise in height, so that over the high ground, temperatures are generally colder. There is also a small latitudinal lapse rate in winter from south to north in Great Britain of 0.2°C per 100 km (derived from Averages of Temperature for Great Britain and Northern Ireland, 1921-50, Meteorological Office, 1953). To a large extent, winter temperature in the British Isles is influenced by the surface temperature of the surrounding sea, and as the North Sea is cooler than the waters off the west coast, the east coast is generally slightly cooler in winter than the west coast. In general, January and February are the coldest months. The daytime maximum temperatures over low ground in January and February average around 5 to 7°C, but on rare occasions in the lee of high ground, temperatures can reach up to around 15°C when a moist south or south-westerly airflow warms up after crossing the mountains, an effect known as a föhn wind.

Maximum and minimum temperatures normally occur inland, away from the moderating influence of the sea. July and August are normally the warmest months, but few places in Scotland have more than one or two days in a year with temperatures greater than 25°C (Parker 1985). Minimum temperatures are very dependent upon local topography and marked differences can occur over relatively short distances. The lowest values tend to occur on clear, still nights where cool air collects at the bottom of valleys.

2.3.3 Sunshine

Scotland is generally cloudy, due mainly to its hilly nature and close proximity to low-pressure systems from the Atlantic. Mountainous areas are dullest, with an annual average of less than 1,100 hours of sunshine over the mountains of the Highland region (Figure 21). For comparison, the south coast of England achieves over 1,700 hours. Maximum mean daily sunshine figures occur in May or June, the minimum occurs in December. The higher latitude at Lerwick, in Shetland, means it receives about four hours more daylight (including twilight) at midsummer than London. Hours of sunshine and temperature are related, but few studies have compared the former with climate proxies. McCarroll *et al.* (2003) showed some proxies yielded higher correlations with sunshine than with temperature.

2.3.4 Wind

Scotland has a severe wind climate compared to the rest of Europe (Figure 18). Scotland's geographical position relative to the track of most Atlantic depressions means that wind is a strong component of its climate. Strong winds typically result from the passage of approximately 150 Atlantic depressions each year, which form in the Atlantic (on the polar front) and cross from west to east. Air circulation around a depression is anti-clockwise and the strongest winds commonly occur to the west and south of its centre. The most common winds (called the prevailing winds) are from the west or south-west. These winds pick up moisture as they cross the Atlantic Ocean. Winds are generally strongest in the winter months, but there is substantial variability in the timing and magnitude of storms from year to year.

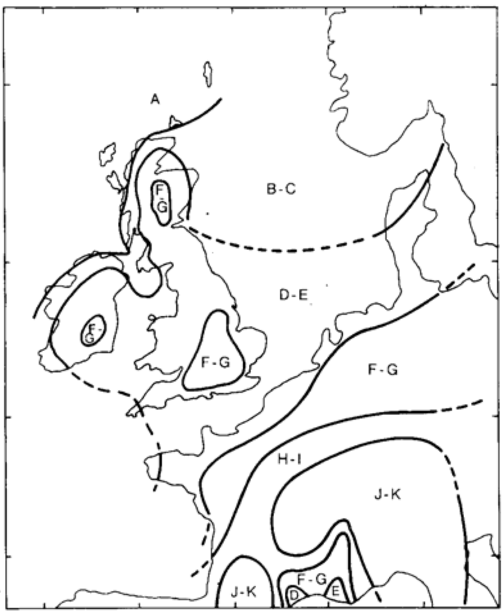


Figure 18: Wind zonation of Europe in the manor of the British windthrow hazard classification system, which is on a scale of A (most windy) to K (least windy). Source: Quine (1995)

Parker (1985) identifies wind as perhaps the most significant element of Scotland’s climate. The south-west is the most common direction from which windthrow occurs, but the wind direction may change markedly from day to day with the passage of weather systems. There is a close relationship between surface isobars (lines joining points of equal air pressure) and the wind speed and direction over open, level terrain. However, in mountainous areas, local topography also has a significant effect, with winds tending to blow along well-defined valleys. It is well known that wind exposure levels tend to increase with increasing site elevation and with increasing proximity to the coast (Grace 1977). Topographical effects are of particular importance and can have a significant influence according to wind direction. A particular valley may offer shelter from one direction, but cause acceleration due to funnelling from another. Windless nights are also an important factor in the occurrence of frost (Figure 22).

The north coast of Scotland has an annual average wind speed of 30 km per hour. North-easterly gales normally occur in spring and north-westerly gales in autumn (Figure 23). Northern Scotland is close to the main storm tracks of the Atlantic, so storms as severe as October 1987 can be expected over the Hebrides, Orkney and Shetland once every 30 to 40 years. Stornoway on Lewis may expect an average of twenty days of gales a year. A day of gale is defined as a day on which the mean wind speed at the standard measuring height of 10 m above ground attains a value of 17.2 metres per second (39 miles per hour, 34 knots) or more over any period of 10 minutes during the 24 hours (http://www.metoffice.gov.uk/) In Shetland the figure is nearer 50 days (for comparison London may experience just two). The highest gust of wind recorded at a low-level site was 229 km.p.h. at Fraserburgh in Aberdeenshire on 13 February 1989. The highest gust recorded at a high-level site was 278 km.p.h. at the Cairngorm Automatic Weather Station at an altitude of 1,245 m on 20 March 1986.

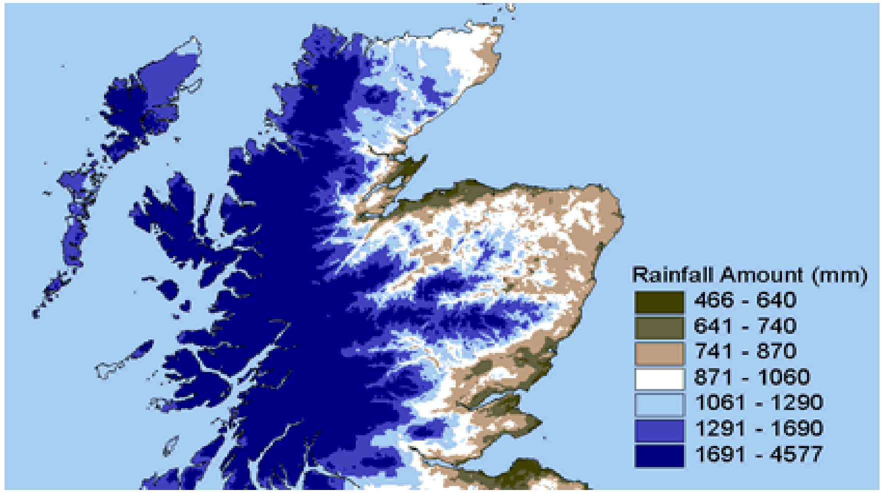


Figure 19: Total yearly rainfall (mm) - Average 1971 - 2000 Source: Met Office (www.metoffice.gov.uk).

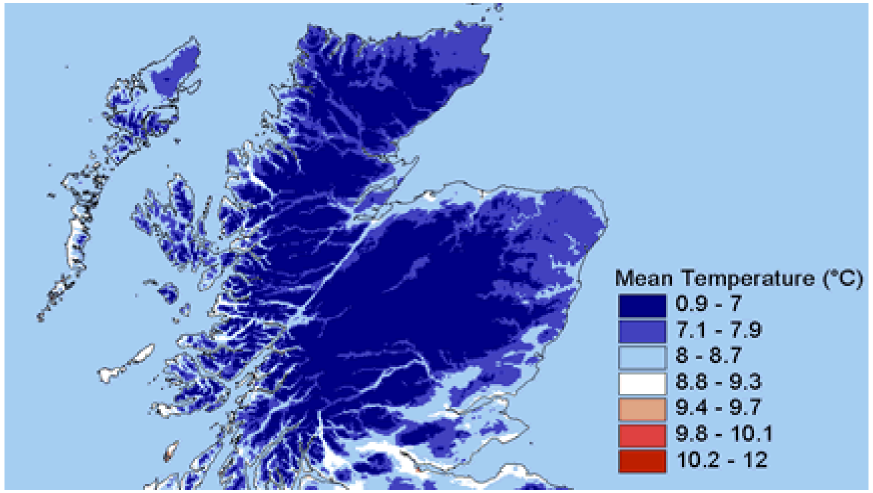


Figure 20: Mean temperature (ºC) - Annual Average 1971 - 2000. Source: Met Office (www.metoffice.gov.uk).

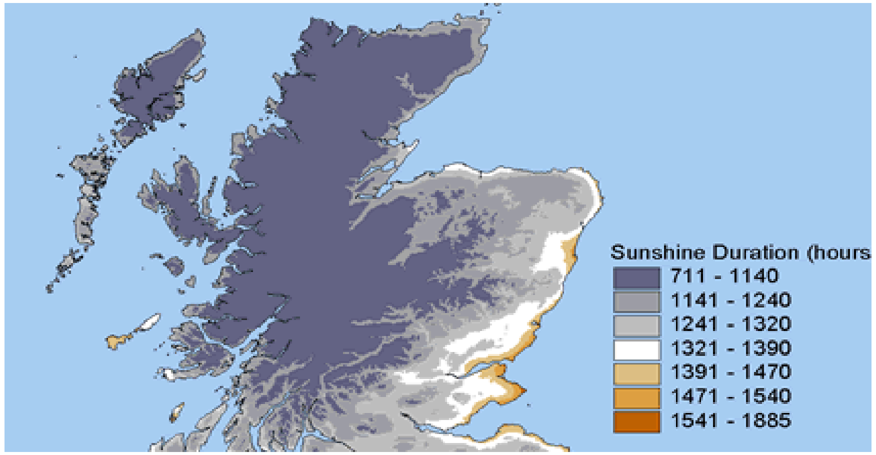


Figure 21: Sunshine Duration (hours) - Annual Average 1971 - 2000. Source: Met Office (www.metoffice.gov.uk).

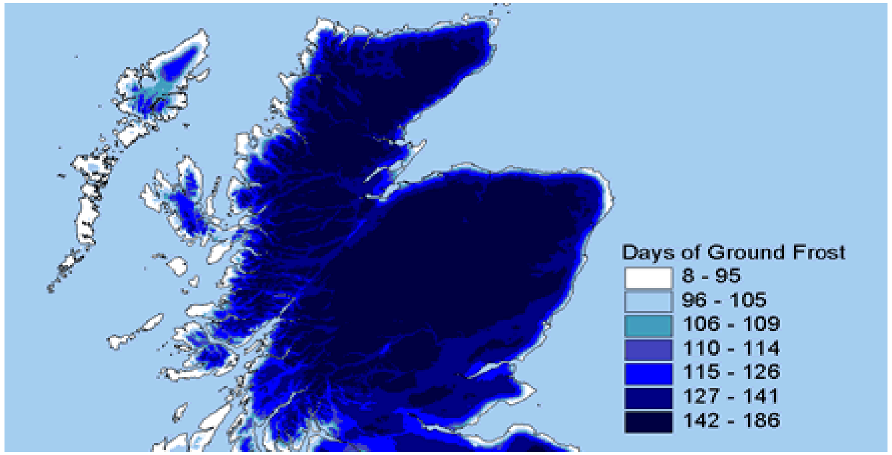


Figure 22: Days of Ground Frost - Annual Average 1971 - 2000. Source: Met Office (www.metoffice.gov.uk).

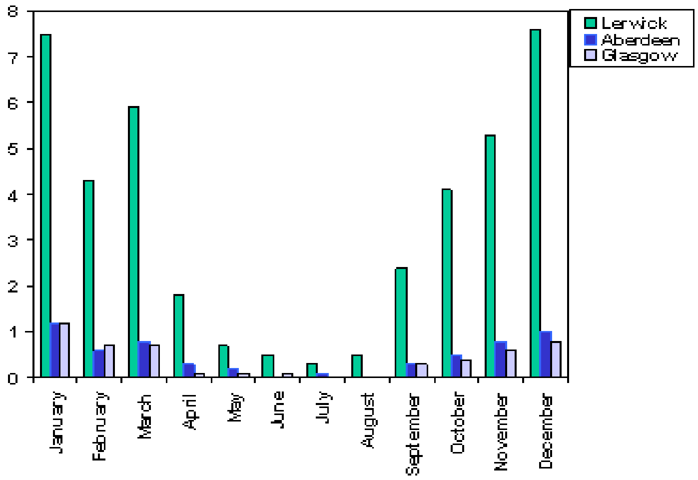


Figure 23: 30-year (1961-90) average number of days with gales for selected stations. Source: Met Office (www.metoffice.gov.uk).

2.3.5 North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is one of the Northern Hemisphere's major multi-annual climatic fluctuations (Appenzeller 1999). NAO indices are calculated by computing the difference in the sea level pressure between the Azores and Iceland, or other near equivalent locations. The sea level pressure for Iceland is subtracted from that of the Azores; a high positive NAO Index implies a large difference between the air masses and an increase in the western (maritime) winds of northern Europe. This relationship is most pronounced in winter and early spring and substantially weaker in summer (Rogers 1984). The stronger the wind, the more of the Gulf Stream’s heat is delivered to Britain, therefore seasons of high positive NAO are associated with warming and increased rainfall over northwest Europe (Hurrell 1995, Jones *et al.* 2001). Exceptionally cold winters are linked to average NAO Index values < -2 (weaker westerlies and even easterlies during part of the season) and exceptionally mild winters are linked to NAO Index values >2 (strong westerlies).

The mild winters of the 1980s and early 1990s in Britain were a time of significantly positive NAO Index. In the negative phase, the Icelandic low becomes displaced south-westwards, and a blocking situation develops around the British Isles with the polar high pressure penetrating southwards. The exceptionally cold winters of 1962/63 and 1941/42 are examples of this negative phase. An increased frequency of gales (associated with an increase in westerly airflows) has occurred across the British Isles with all months of the year receiving 5-25% more westerlies during 1981-1992 than during 1951-1980 (Mayes 1994). Gale frequency in southern Scotland was extremely high between 1813 and 1843 with peak storminess around 1820 (Dawson *et al.* 1997). There are several NAO indices available, obtained by slightly different calculation methods and from different climate stations (Rogers 1984, Hurrell 1995, Jones *et al.* 1997, Luterbacher *et al.* 1999)

2.3.6 Ecological areas

The two maps of Birse and Dry (1970) and Birse and Robertson (1970) are combined to construct a map of bioclimatic sub-regions (Birse 1971). Thermal zonation, oceanicity and moisture status are determinants of the bioclimatic zones. These categories are used as ecologically relevant subdivisions of climate for blanket bog and pine tree development and differentiation. Precipitation, humidity and cloud cover increase with altitude, while temperature and evapo-transpiration decrease. Other factors being equal, there is thus a tendency for increasing altitude to favour blanket bog development. The reduction in temperature with increasing altitude also affects plant growth directly. Birse (1971) used accumulated temperature in day-degrees as a measure of temperature for plant growth. In Caithness and Sutherland an accumulated temperature of 275-550 day°C is estimated for the highest ground (e.g. Ben More Assynt). On the coasts and in north-east Caithness, the figure is 1100-1375 day°C. Most of the peatland area occurs well within these two extremes at 825-1100 day°C (Birse and Dry 1970). Birse and Robertson (1970) consider exposure and accumulated frost; both factors attain moderate values for the majority of peatland area. Exposure increases towards the west coast. Winters are very mild on all coasts, but especially the west. Altitude increases both exposure and frost. The winters are mild in Caithness and Sutherland compared to the rest of Scotland, especially the Grampian Highlands, but exposure is generally more severe.

Oceanicity is the degree to which the climate of a place is influenced by the moderating influence of the ocean. Its converse is continentality which is a measure of the degree to which the climate of a region typifies that of the interior of a large landmass. Regions with high oceanicity usually experience mild winters and cool summers, while regions with high continentality tend to experience hot summers and colder winters. The length and intensity of the growing season are influenced by the distance to the sea. It is also related to windiness at a regional scale, atmospheric humidity and accumulated frost. Birse (1971) divides Scotland into 3 sub-sectors based on oceanicity (O1 = Hyperoceanic, O2 = Euoceanic and O3 = Hemioceanic). Class O1 is the most oceanic and has the smallest range of annual temperature and, other factors being equal (e.g. latitude, elevation and topographic shelter), is the windiest, has the longest growing season, has the highest atmospheric humidity, and the smallest accumulated frost. Class O3 is the most continental and, again other factors being equal, is the least windy, has the shortest growing season, the lowest humidity and the largest accumulated frost.

Different sites respond differently to precipitation, which has clear implications for the possibility of climate-driven drying of bog surfaces. Lindsay (1995) provides a useful division of blanket mires into six sub-categories (based on topography and hydromorphology), which was used where appropriate.

2.4 Dendroclimatological analysis

The most common statistical models used by dendrochronologists to examine the relationships between tree-ring width and climate are called "correlation functions" and “response functions" (Fritts 1971, Blasing *et al.* 1984). The term "function" indicates a sequence of coefficients computed between the tree-ring chronology and monthly climatic variables. In correlation functions the coefficients are univariate estimates of Pearson's product moment correlation, e.g. Morrison (1983), while in response functions the coefficients are multivariate estimates from a principal component regression model (Briffa and Cook 1990). Correlation functions can incorrectly be tested for significance, as explained by Biondi (1997). Similarly, in response functions normal significance levels of coefficients can be misleading because errors are underestimated (Morzukh and Ruark 1991), and hence some coefficients can erroneously pass the significance test. Due to these possible errors, it is desirable to compute bootstrapped confidence intervals for both correlation and response functions (Biondi and Waikul 2004).

The relationship between monthly climate variables (such as temperature and precipitation) and annual ring width are examined using a computer program called DENDROCLIM2002 (Biondi 1997, Biondi 2000). The program uses bootstrapped samples to compute both correlation and response coefficients and for single and multiple periods, and to test their significance at the 0.05 level (Biondi and Waikul 2004).

2.4.1 Selection of a “biological year” window for *Pinus sylvestris*

Comparisons between different studies on the climatic response of pine are complicated by the lack of common methodologies and particularly differences in the ranges of months analysed. Earlier studies highlight that prior growth in pine has a significant effect and therefore the range of months examined often starts in the previous year. However, as standardisation methods largely remove the autocorrelation effect of prior growth in the residual chronology, the windows of analysis should not be longer than 12 months. Researchers on Scots pine in Scandinavia (Linderholm 2001) select a 12 month window, which ranges from the prior September to the August of the current year. Carrer (2006) selects months according to the "biological" year frequently adopted for Alpine species studies. Their 12 month window for analysis ranges from October of the year prior to growth, to September of the year of growth. Grace and Norton (1990), in the most recent study of pine in Scotland, selected a 12 month window from the November of the year prior to growth to October in the year of growth. It was considered useful for comparisons to use a window close to that of Grace and Norton, but the growing season of pine in the region was another consideration.

In the high, cool regions of the Highlands, Schweingruber *et al.* (1979) identified the development of the annual ring in conifers to begin approximately in July and end in September. Significantly though, in the maritime climate of western Scotland, high temperatures from June to October appear to promote a corresponding relatively long growth period (4-5) months in conifers. Given the possible growing season of Scots pine in western Scotland to October and that, since 1961, Scotland has seen the length of growing season increase by more than 4 weeks (Barnett *et al.* 2006), it was considered sensible to extend the 12 month window to November of the current year. This study therefore uses a 12 month window, ranging from December of the year prior to growth, to November of the year of growth. The month selected from the prior year is generally distinguished in figures by the capitalised abbreviations e.g. DEC, the current years are abbreviated with small letters e.g. Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct and Nov.

2.4.2 Evolutionary and moving response and correlation function analysis

As climate changes, the relationships between ring width and monthly climate variables are likely to alter with time. The program DENDROCLIM2002 has a significant advantage over earlier response function analysis e.g. PRECON (Fritts 1999) because it enables the relationship of climate variable with ring width to be examined over time, allowing the temporal stability of relationship to be assessed. The program enables three methods of analysis to examine the stability of responses over time:

1) *Forward evolutionary intervals, in which the start year of the interval remains the same and for each calculation the end year is incremented by one, so that the intervals go progressively forward in time.*
2) *Backward evolutionary intervals, in which the end year of the interval remains the same, and for each calculation the start year is decreased by one, so that the intervals go progressively backward in time.*
3) *Moving intervals, in which a constant length of tree-ring data (beginning with the oldest year) is progressively shifted forward one year at a time to the most recent year.*

A problem with both methods of evolutionary intervals is that unless all the data are reduced to a common selected interval, the start and end for different sets of data make it difficult to compare their results. Also when a sudden change in a relationship occurs it is “blurred” by the weight of the preceding or following interval and therefore difficult to identify precisely when the change occurred. Due to these factors, moving interval correlation function analysis (or moving correlation functions) was selected as the most suitable method of analysis for examining relationships between tree-ring and climatic variables.

2.4.3 Selection of a standard window for response and correlation analysis

Briffa and Cook (1990) caution that comparing the results of response function analysis of different chronologies (or for the same chronology over different periods) is fraught with problems: whether or not one wishes to compare the overall amount of chronology variance explained by climate (R^2) or the character of the tree/climate relationship in terms of significant response function coefficients. To guard against the possibility of over-calibrating the response functions, it is important that the number of annual climate observations exceeds, as far as possible, the number of candidate predictors. They also emphasise the importance of using a common method to enable more valid comparisons. These factors are considered equally applicable to correlation functions. To assist comparison between data sets, a "standard" base length for moving correlation functions is advantageous. However, in selecting the size for the base length for analysis, there are a number of considerations.

A restriction of DENDROCLIM2002 is that the base length (L) must be less than 80% of the available years and must not be less than twice the number of predictors. Increasing the base length increases the number of predictors required and hence a longer sequence of years is required. Short base lengths have the advantage that they allow the use of shorter sequences of climatic data, however a disadvantage is the period might contain too few years to identify significant relationships with monthly data. Longer base lengths have the disadvantage that they require longer sequences of climatic data which are not always available from climate stations, preventing their use in analysis, but longer periods are more likely to contain sufficient years to identify significant relationships with monthly data, assuming the relationships are stable. A 12-month window from December of the previous year, to November of the current year was selected; therefore the minimum sequence length that the analysis could be run on was 32-years. An 80-year base length was selected for all correlation, response function and moving correlation functions. Predominantly stable relationships are defined as those occurring over about 50% of the base length. Where changes of relationship in moving correlation functions were identified, the actual date of change is identified as 40 years prior or subsequent to the actual start or end date respectively indicated, due to the 80-year base length used, i.e. half way along the base length used.

2.4.4 Pointer years

The aim of this pointer year analysis is to detect populations that respond in a similar way to prevailing environmental factors. Pointer years are caused by the reaction of trees to certain environmental conditions that favour or limit growth and therefore can be useful as ecological indicators (Schweingruber 1996). The analysis of pointer years can constitute a useful tool for the study of small areas (Schweingruber *et al.* 1991), and/or larger scale geographical areas (Kelly *et al.* 1989). A wide number of expressions have been used for calendar years of remarkable interest within a single series or a set of tree-ring series (Schweingruber *et al.* 1990). Kaennel and Schweingruber (1995) revised these terms and define pointer years (i.e years showing pointer values) as years in which a specific proportion of the series have extremely high or low values of the same sign.

A computer program called WEISER (González 2001) was used to establish pointer years from raw tree-ring data (Schweingruber *et al.* 1990, Desplanque *et al.* 1999). In this research the analysis was performed over the period 1880–1980 (except where shortness of the tree-ring data forced a reduced period). Due to 17 chronologies ending between 1976 and 1980, only pointer years calculated between 1880 and 1976 were used in most comparisons. Pointer values correspond to the year in which a set proportion of the series show extreamly high or low values of the same sign in the same year (Schweingruber *et al.* 1990). The term pointer interval corresponds to the year in which, the growth of a significant proportion of trees show the same downward or upward trend from the previous year (Schweingruber *et al.* 1990). Pointer values were set at 50% and pointer intervals set at 75%. These criteria were combined to establish both positive and negative pointer years for each chronology. A total of 26 Scots pine chronologies were analysed. Where pointer years of the same sign affect four or more mineral substrate chronologies in the NW area, or five or more in the SE area they were identified as generally affecting the whole area, these criteria identifying 49 and 53 years for each respectively area. Where pointer years of the same sign affect both the NW and SE areas these years were identified as pointer years generally affecting Scots pine in Northern Scotland.

2.4.5 Simple correlation

Moving correlation functions suggested changes to the response to climate occurring in some chronologies around 1920. To further investigate a possible change in the response of Scots pine to climate, correlation analysis was performed over two separate periods 1881-1930 and 1831-1980. Pointer years were developed into a numerical sequence for comparison in this analysis called POINT-YR. Negative pointer years were given the value 50, positive pointer years given the value 150 and all other rings given the value of 100 in this sequence. Simple correlation is used to identify these changes in climatic variables associated with tree growth, but it should be recognised that this method has the potential disadvantage that these variables may be highly correlated with each other, as well as with growth (Fritts 1966). Positive intercorrelations can increase the simple correlation values between some non-casual factors and growth, whereas negative intercorrelations can decrease the simple correlation between important casual factors and growth.

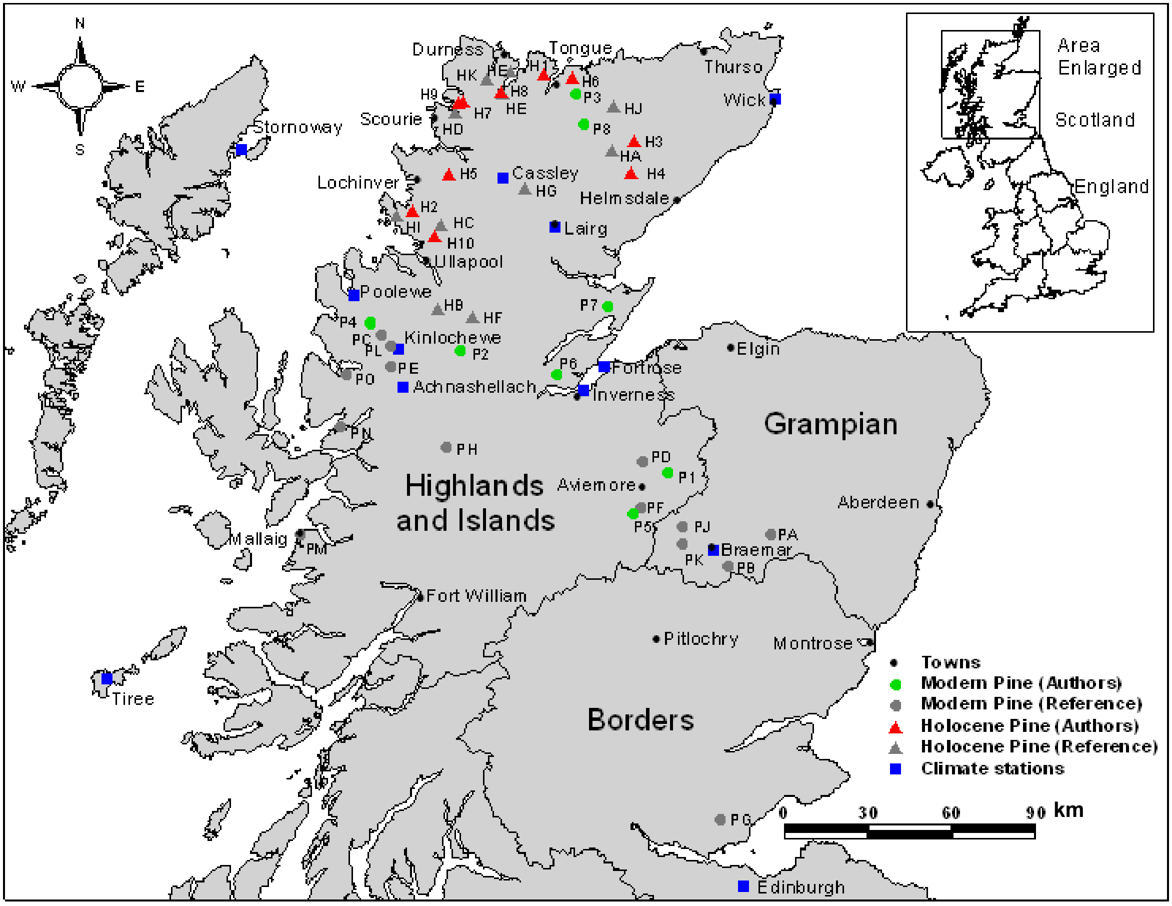
2.5 Radiocarbon dating analysis

Where uncalibrated radiocarbon dates were available they have been calibrated using OXCAL 4.0 (Bronk Ramsey 1995, 2001). The IntCal04: Northern Hemisphere curve (Reimer *et al.* 2004) was used for calibration. The 95.4% range of calibrated dates (also called the 2σ range of dates) rounded to the nearest 50 years are quoted as ^{14}C cal. yr BC (Bronk Ramsey 2001). The wiggle-matching of tree-ring sequences was performed using OXCAL 4.0 (Bronk Ramsey *et al.* 2001).

To help confirm the technique of cross-matching of subfossil Scots pine, a sample from Strath Kanaid and one from Loch an Ruathair were submitted for radiocarbon dating at the ^{14}CHRONO Centre (Queen's University of Belfast). The samples submitted for dating were taken from rings 30-50 of SMUR20 and rings 40-60 of RATH12.

3 RESULTS AND INTERPRETATION

This chapter presents the results and interpretation of the sites studied. First the modern sites are detailed in alphabetical order, followed by the subfossil pine sites, in similar order. For each of the main sites sampled, a brief description and its location is given, followed by the results of the dendrochronological analysis. The location of individual samples, where recorded, are presented in Appendix II. The cross-matching between samples for each chronology established are presented in Appendix III. The stand dynamics are derived from the bar diagram with pith information (Appendix IV), plots of the tree-ring series (Appendix V & Appendix VI) and decadal radial growth histograms (Appendix VII & Appendix VIII). This is followed by the inter-site comparisons (Section 3.3) and climate analysis (Section 3.4). Raw tree-ring data for the regional reference chronologies established are shown in Appendix IX. The moving correlation functions and simple correlation data used in the climate analysis are shown in Appendix XI. The location of pine sites and climate stations are shown in Figure 24.



KEY

Modern Pine (Author)		Modern Pine (Reference)		Holocene Pine (Author)		Holocene Pine (Reference)	
P1	Abernethy	PA	Alltcailleach Forest	H1	An Dubh-loch	HA	Badanloch
P2	Achanalt	PB	Ballochbuie	H2	Druim Bad a' Ghaill	HB	Fain
P3	Borgie Forest	PC	Beinn Eighe	H3	Loch an Ruathair	HC	Knockanrock
P4	Eilann Subhainn	PD	Carrbridge	H4	Loch Ascaig	HD	Laxford Bridge
P5	Inshriach	PE	Coulin	H5	Loch Assynt	HE	Loch Eriboll
P6	Monadh Mor	PF	Creag Fhiaclach	H6	Loch Crocach	HF	Loch Glascarnoch
P7	Pitmaduthy	PG	Dimmie	H7	Loch na Thull	HG	Loch Shin
P8	Strathnaver	PH	Glen Affric	H8	Polla on Loch Eriboll	HH	Loch Sian
		PJ	Glen Derry	H9	Skerricha	HI	Loch Vatachan
		PK	Inverey	H10	Strath Kanaird	HJ	Lochstrathy
		PL	Loch Maree			HK	Srath Dionard
		PM	Mallaig, Loch Morar				
		PN	Plockton				
		PO	Shieldaig				

Figure 24: A map of northern Scotland showing the location of most Modern and Holocene pine chronologies, together with climate stations used in this research.

3.1 Modern Scots pine sites

A total of 197 modern Scots pine trees were sampled in the course of this study, of these 6% were unmeasured, 19% unmatched and 75% could be cross-matched. Nine Modern tree-ring chronologies from peat and nine from mineral substrates were developed (Figure 25). Tree-ring data from 196 trees from earlier studies were also acquired and nineteen references chronologies established. All tree-ring chronologies were developed and analysed using common methodologies. Due to the ring-width data for the Creag Fhiaclach and Carrbridge having been truncated at 1880, (and therefore without pith information), these sites were excluded from age growth trend plots.

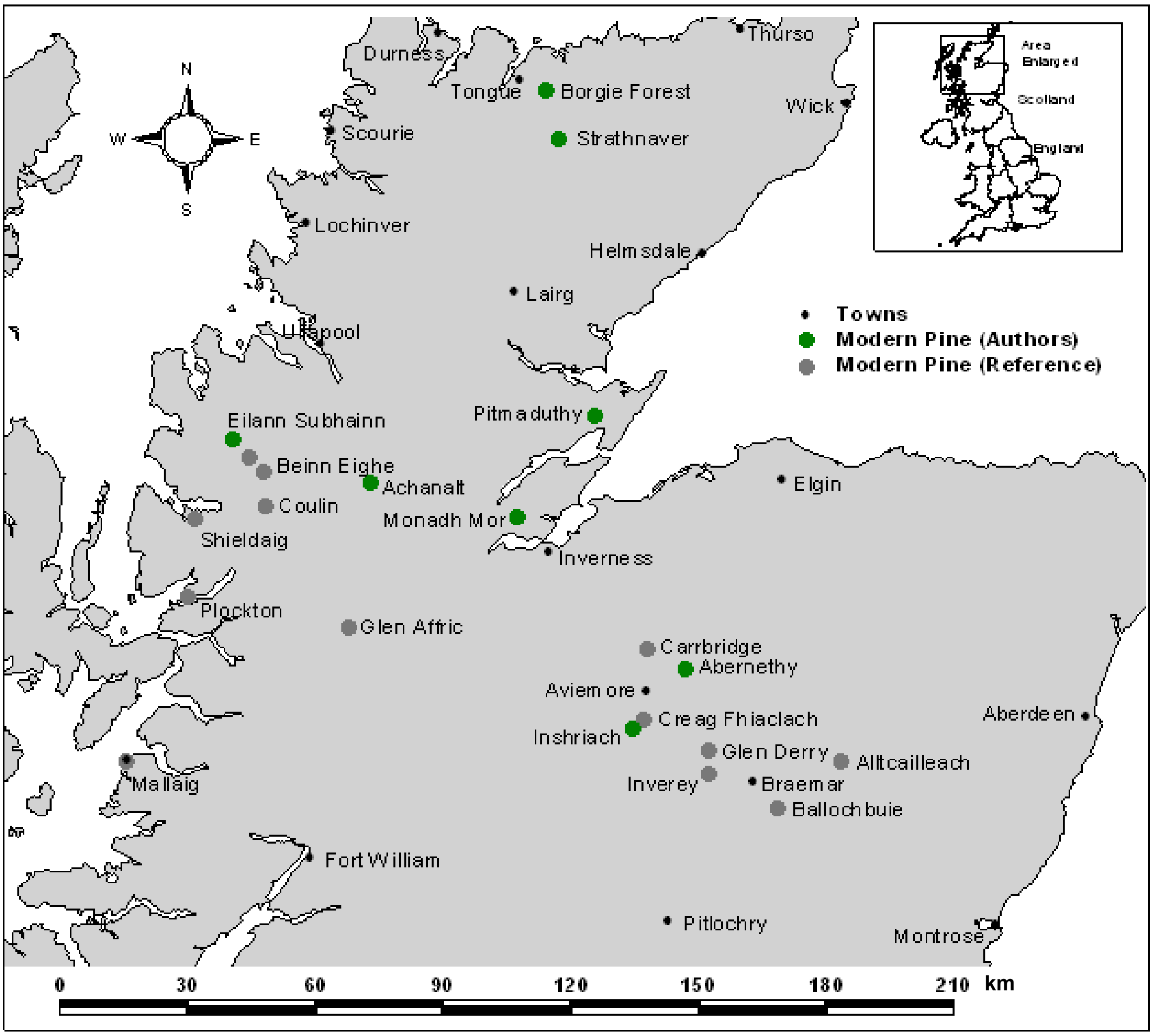


Figure 25: A map of northern Scotland showing the modern Scots pine tree-ring chronologies used in this study.
Dimme lies 60 km south of Pitlochry and is not shown.

Summaries of the Modern Scots pine tree-ring chronologies developed in this research, followed by reference chronologies are listed alphabetically in Table 2.

Table 2: Summary table of the modern Scots pine chronologies of northern Scotland

Map Key	Site name	Latitude (dec. deg.)	Longitude (dec. deg.)	Altitude (m)	Site Type	Mean depth of peat (m)	Mean sample height (m)	Trees Sampled	Cross-matched trees	Success rate	Mean cross-matching (*t*-value) (correlation)	Chronology name (site code)	MR	MS	AC	Mean Age	SD	Chronology Span	Chronology length (yr.)	Oldest tree at site (yr.)	Short Reference
P1	Abernethy - B	57.24	-3.68	220	Wooded bog	4.86	0.25	6	6	100%	4.26	ABEB-6	0.44	0.22	0.92	145	24	AD1694-AD2000	307	337	(Author, this thesis)
P1	Abernethy - A	57.24	-3.68	220	Wooded bog	4.22	0.25	16	16	100%	3.70	ABEA-16	0.65	0.16	0.77	177	29	AD1798-AD2000	203	220	(Author, this thesis)
P1	Abernethy - C	57.24	-3.68	220	Wooded bog	4.66	0.25	23	21	91%	3.61	ABEC-21	0.69	0.17	0.85	148	20	AD1838-AD2000	163	173	(Author, this thesis)
P1	Abernethy - D	57.24	-3.68	220	Mineral	0.00	0.25	10	9	90%	3.18	ABED-9	1.75	0.17	0.84	74	22	AD1882-AD2000	119	129	(Author, this thesis)
P2	Achanalt	57.61	-4.94	130	Mineral	0.00	0.10	8	7	88%	4.51	ACHA-7	1.80	0.17	0.75	116	1	AD1893-AD2004	112	117	(Author, this thesis)
P3	Borgie Forest	58.45	-4.30	200	Mineral	0.00	0.84	10	9	90%	3.58	BODG-9	2.86	0.18	0.93	45	2	AD1964-AD2005	42	51	(Author, this thesis)
P4	Eilann Subhainn - A	57.69	-5.49	50	Wooded bog	0.35	0.50	14	9	64%	3.83	ESBE-9	0.93	0.20	0.86	101	33	AD1869-AD2005	137	147	(Author, this thesis)
P4	Eilann Subhainn - B	57.69	-5.49	50	Wooded bog	0.84	0.73	13	12	92%	4.55	ESDB-12	1.00	0.19	0.76	164	45	AD1790-AD2005	216	226	(Author, this thesis)
P4	Eilann Subhainn - C	57.69	-5.49	50	Mineral	0.00	0.87	13	13	100%	4.21	ESDG-13	0.85	0.20	0.93	122	38	AD1837-AD2005	169	187	(Author, this thesis)
P5	Inshriach - A	57.11	-3.88	300	Cutover bog	0.35	0.25	7	3	43%	2.66	INSH-M1	2.97	0.13	0.77	55	3	AD1953-AD1999	47	57	(Author, this thesis)
P5	Inshriach - B	57.11	-3.88	300	Mineral	0.00	0.25	6	2	33%	3.99	INSH-M2	2.35	0.15	0.81	51	1	AD1958-AD1999	42	52	(Author, this thesis)
P6	Monadh Mor - A	57.55	-4.36	200	Wooded bog	0.75	0.25	6	6	100%	3.33	MONM-M1	1.67	0.15	0.86	99	6	AD1906-AD1999	94	109	(Author, this thesis)
P6	Monadh Mor - B	57.55	-4.36	200	Wooded bog	0.75	0.25	4	4	100%	3.82	MONM-M2	1.33	0.18	0.85	72	5	AD1934-AD1999	66	76	(Author, this thesis)
P7	Pitmaduthy - B	57.77	-4.07	100	Mineral	0.00	0.25	6	6	100%	4.44	PITM-M2	2.36	0.17	0.82	138	5	AD1938-AD1999	62	74	(Author, this thesis)
P7	Pitmaduthy - A	57.77	-4.07	100	Wooded bog	?	0.25	12	12	100%	5.68	PITM-M1	0.83	0.20	0.78	117	12	AD1875-AD1999	125	136	(Author, this thesis)
P8	Srathnaver Forest- A	58.35	-4.24	25	Blanket peat	0.77	1.30	10	0	0%		STPE-10	2.25	0.13		41	4	AD1965-AD2005	40	46	(Author, this thesis)
P8	Srathnaver Forest - B	58.35	-4.24	25	Mineral	0.00	0.69	10	6	60%	4.25	STWB-6	1.84	0.25	0.86	42	3	AD1965-AD2005	41	46	(Author, this thesis)
P8	Srathnaver Forest - C	58.35	-4.24	25	Mineral	0.00	0.80	10	7	70%	3.33	STIN-7	2.64	0.20	0.92	45	1	AD1966-AD2005	40	48	(Author, this thesis)
PA	Alltcailleach Forest	57.05	-3.07	300	Mineral	0.00	1.30	32	32									AD1883-AD1972			(Miller 1976)
PB	Ballochbuie	56.95	-3.32	380	Mineral	0.00	1.30	11	11	100%	5.84	BALLOCHB	1.38	0.13	0.93	255	19	AD1712-AD1978	267	282	(Hughes 1984; Hughes 1987)
PC	Beinn Eighe	57.62	-5.36	300	Mineral	0.00	1.30	17	10	59%	3.60	BNAA-10	1.03	0.16	0.90	170	24	AD1809-AD1989	181	196	(Barlow 1990)
PD	Carrbridge	57.28	-3.83	270	Mineral/Managed	0.00	1.30	13	13	100%	4.07	CFG-13	1.46	0.13	0.93			AD1880-AD1979	100	120	(Grace 1990)
PE	Coulin	57.55	-5.35	250	Mineral	0.00	1.30	11	11	100%	4.56	COULIN	1.18	0.13	0.90	243	62	AD1671-AD1978	308	323	(Hughes 1984; Hughes 1987)
PF	Creag Fhiaclach - F	57.13	-3.84	280	Mineral/Waterlogged	?	1.30	11	11	100%	3.68	CFF-11	1.57	0.12	0.82	150	?	AD1880-AD1979	100	150	(Grace 1990)
PF	Creag Fhiaclach - E	57.13	-3.84	400	Mineral/Sloping	0.00	1.30	11	9	82%	3.50	CFE-9	0.72	0.14	0.52	290	?	AD1880-AD1979	100	330	(Grace 1990)
PF	Creag Fhiaclach - D	57.13	-3.84	450	Mineral/Sloping	0.00	1.30	11	11	100%	5.32	CFD-11	0.48	0.16	0.59	270	?	AD1880-AD1979	100	430	(Grace 1990)
PF	Creag Fhiaclach - A	57.13	-3.84	500	Mineral/Sloping	0.00	1.30	15	15	100%	6.17	CFA-15	1.09	0.13	0.59	205	?	AD1880-AD1979	100	260	(Grace 1990)
PF	Creag Fhiaclach - B	57.13	-3.84	550	Mineral/Sloping	0.00	1.30	10	10	100%	5.24	CFB-10	1.03	0.14	0.62	195	?	AD1880-AD1979	100	270	(Grace 1990)
PF	Creag Fhiaclach - C	57.13	-3.84	600	Mineral/Sloping	0.00	1.30	5	3	60%	4.74	CFC-3	0.86	0.22	0.86	175	?	AD1880-AD1979	100	250	(Grace 1990)
PG	Dimmie	56.13	-3.33	200	Mineral/Flat	0.00	1.30	12	12	100%	5.71	DIMMIE	1.88	0.16	0.72	147	19	AD1828-AD1976	149	164	(Hughes 1987)
PH	Glen Affric	57.30	-5.00	300	Mineral	0.00	1.30	13	13	100%	4.12	GLNAFRIC	1.04	0.13	0.86	202	31	AD1735-AD1976	242	257	(Hughes 1984; Hughes 1987)
PJ	Glen Derry	57.07	-3.59	400?	Mineral	0.00	1.30	13	13	100%	6.60	GLENDERRY	1.36	0.13	0.90	194	25	AD1773-AD1978	206	221	(Hughes 1984)
PK	Inverey	57.02	-3.58	500	Mineral	0.00	1.30	13	13	100%	6.53	INVEREY	1.23	0.12	0.93	232	56	AD1706-AD1976	271	286	(Hughes 1984; Hughes 1987)
PL	Loch Maree	57.65	-5.42	100	Mineral	0.00	1.30	8	8	100%	3.94	LCHMAREE	1.00	0.16	0.86	172	52	AD1756-AD1978	223	238	(Hughes 1984; Hughes 1987)
PM	Mallaig, Loch Morar	57.00	-5.84	100	Mineral	0.00	1.30	13	10	77%	3.61	MALLAIG	3.55	0.12	0.70	73	11	AD1903-AD1976	74	89	(Hughes 1984)
PN	Plockton	57.35	-5.63	100	Mineral	0.00	1.30	13	12	92%	3.60	PLOCKTON	2.40	0.12	0.90	99	10	AD1879-AD1976	98	113	(Hughes 1987)
PO	Shieldaig	57.52	-5.62	10	Mineral/Sloping	0.00	1.30	11	11	100%	4.10	SHIELDAG	2.06	0.12	0.88	126	16	AD1847-AD1978	132	147	(Hughes 1987)

KEY: MR = mean ring width, MS = Mean sensitivity, AC = Auto correlation, SD = Standard deviation and underlined = estimated or quoted from other published results

Where Modern data are compared it is listed broadly from the north-west to the south-east. However, to further assist visual comparison, similar substrate sites are grouped and consideration given to altitude (see Table 3). The sites are generally listed in this same order throughout this study to help identify regional patterns.

Table 3: Scottish sites of Modern Scots pine used in this study, broadly listed on a north-west to south-east transect, but with consideration to site type and altitude. Oceanicity and climate conditions are also shown (Birse 1971).

Order	**Site name**	**Site**	**Latitude (dec. deg.)**	**Longitude (dec. deg.)**	**Altitude (m)**	**Oceanicity**	**Bioclimatic sub-region**
1	Borgie Forest	Mineral	58.45	-4.30	200	2	h2b2
2	Srathnaver Forest - B	Mineral	58.35	-4.24	25	2	h2b3
3	Srathnaver Forest - C	Mineral	58.35	-4.24	25	2	h2b3
4	Srathnaver Forest- A	Peat	58.35	-4.24	25	2	h2b3
5	Eilann Subhainn - A	Peat	57.69	-5.49	50	1	h1b2
6	Eilann Subhainn - B	Peat	57.69	-5.49	50	1	h1b2
7	Eilann Subhainn - C	Mineral	57.69	-5.49	50	1	h1b2
8	Loch Maree	Mineral	57.65	-5.42	100	2	pb2
9	Beinn Eighe	Mineral	57.62	-5.36	300	2	pa3
10	Coulin	Mineral	57.55	-5.35	250	2	pb3
11	Achanalt	Mineral	57.61	-4.94	130	2	h1b3
12	Shieldaig	Mineral	57.52	-5.62	10	1	h1b3
13	Plockton	Mineral	57.35	-5.63	100	1	h1b3
14	Mallaig, Loch Morar	Mineral	57.00	-5.84	100	1	h1b3
15	Glen Affric	Mineral	57.30	-5.00	300	2	pa3
16	Pitmaduthy - B	Mineral	57.77	-4.07	100	2	h4t1
17	Pitmaduthy - A	Peat	57.77	-4.07	100	2	h4t1
18	Monadh Mor - A	Peat	57.55	-4.36	200	2	h3b3
19	Monadh Mor - B	Peat	57.55	-4.36	200	2	h3b3
20	Abernethy - B	Peat	57.24	-3.68	220	3	h3b3
21	Abernethy - A	Peat	57.24	-3.68	220	3	h3b3
22	Abernethy - C	Peat	57.24	-3.68	220	3	h3b3
23	Inshriach - A	Peat	57.11	-3.88	300	3	h2b2
24	Inshriach - B	Mineral	57.11	-3.88	300	3	h2b2
25	Abernethy - D	Mineral	57.24	-3.68	220	3	h3b3
26	Carrbridge	Mineral	57.28	-3.83	270	3	h2b2
27	Creag Fhiaclach - F	Mineral	57.13	-3.84	280	3	h2b2
28	Creag Fhiaclach - E	Mineral	57.13	-3.84	400	3	h1a3
29	Creag Fhiaclach - D	Mineral	57.13	-3.84	450	3	h1a3
30	Creag Fhiaclach - A	Mineral	57.13	-3.84	500	3	h1a3
31	Creag Fhiaclach - B	Mineral	57.13	-3.84	550	3	h1a3
32	Creag Fhiaclach - C	Mineral	57.13	-3.84	600	3	h1a3
33	Glen Derry	Mineral	57.07	-3.59	400?	3	h1a2
34	Inverey	Mineral	57.02	-3.58	500	3	h1b1
35	Ballochbuie	Mineral	56.95	-3.32	380	3	h1a2
36	Alltcailleach Forest	Mineral	57.05	-3.07	300	3	h1a2
37	Dimmie	Mineral	56.13	-3.33	200	2	h3t1

Key: O1 = Hyperoceanic, O2 = Euoceanic, O3 = Hemioceanic, p = perhumid, h1 = extremely humid, h2 = very humid, h3 humid, h4 fairly humid, t1 =temperate, b1-b3 = boreal and oroboreal, a1-a3 = Arctic and oroartic.

As a check on the cross-dating and annual resolution, the seventeen chronologies developed were compared against data from other sites in Scotland (Hughes *et al.* 1984, Hughes 1987) as well as three chronologies called LAPLAND, NORW013, NORW014 respectively from Lapland in Sweden (Eggertsson in (Kolström 2002)), Hurdal and Jondalen in Norway (Briffa *et al.* 1988), see Table 4.

Table 4: Cross-matching table of modern *P. sylvestris* chronologies in Scotland, together with three other chronologies

Filenames	Relative location	Altitude (m)	Start date	End date	02	03	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	37	38	39	40
01. BODG-9	North west	200	AD1964	AD2005	-	-	-	-	-	-	-	-	-	-	\	\	\	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	\	-	\	-	-	-
02. STWB-6	North west	25	AD1965	AD2005		4.9	-	-	-	\	-	\	-	\	\	\	\	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	\	\	\	\	-	-	-
03. STIN-7	North west	25	AD1966	AD2005			-	-	-	\	-	\	-	\	\	\	\	-	-	-	-	-	-	-	-	-	-	\	\	\	\	\	\	\	\	\	\	\	-	-	-
05. ESBE-9	North west	50	AD1869	AD2005				7.1	6.2	-	5.5	-	-	3.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
06. ESDB-12	North west	50	AD1790	AD2005					7.2	-	4.4	6.1	4.3	5.1	5.0	-	4.2	-	-	-	-	-	-	-	-	-	-	4.2	-	-	3.6	3.5	-	-	-	-	-	3.8	-	-	3.8
07. ESDG-13	North west	50	AD1837	AD2005						-	3.7	3.6	-	3.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.2
08. LCHMAREE	North west	100	AD1756	AD1978							6.1	6.5	3.8	5.1	6.6	-	5.5	-	-	4.2	-	-	-	-	-	-	-	4.1	3.9	5.7	4.1	4.3	4.6	-	6.7	5.6	5.2	4.4	-	3.7	-
09. BNAA-10	North west	300	AD1809	AD1989								6.2	3.7	5.8	5.7	-	4.7	-	-	-	-	-	-	-	-	-	-	-	-	5.0	-	3.5	3.6	-	3.6	-	-	4.5	-	-	-
10. COULIN	North west	250	AD1671	AD1978									-	-	4.9	-	5.6	-	-	-	-	-	-	-	-	-	-	4.2	-	6.1	4.3	4.8	3.8	-	7.5	8.2	6.1	-	-	5.0	-
11. ACHA-7	North west	130	AD1893	AD2004										-	6.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12. SHIELDAG	North west	12	AD1847	AD1978											4.3	-	4.4	-	-	-	-	-	-	-	-	-	-	-	6.1	4.2	-	4.6	4.3	-	4.4	-	-	3.5	-	-	-
13. PLOCKTON	North west	100	AD1879	AD1976												-	4.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.5	-	-	-	-	-	-
14. MALLAIG	North west	100	AD1903	AD1976													4.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.8	4.5	-	-	4.1	-	-	-
15. GLNAFRIC	North west	300	AD1735	AD1976														-	-	-	-	-	-	-	-	-	-	7.5	6.9	8.1	6.0	9.0	6.9	3.7	8.7	6.2	6.0	-	-	4.0	3.9
16. PITM-M2	South east	100	AD1938	AD1999															-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.4	-	-	-
17. PITM-M1	South east	100	AD1875	AD1999																7.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18. MONM-M1	South east	200	AD1906	AD1999																	-	3.6	4.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19. MONM-M2	South east	200	AD1934	AD1999																		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.8	-	-
20. ABEB-6	South east	300	AD1694	AD2000																			11.5	12.2	-	-	-	5.3	-	-	-	-	-	-	-	-	-	-	-	-	-
21. ABEA-16	South east	300	AD1798	AD2000																				15.6	-	-	-	5.1	-	-	-	-	-	-	-	-	-	-	-	-	-
22. ABEC-21	South east	300	AD1838	AD2000																					-	-	-	5.1	-	-	-	3.7	-	-	-	-	-	-	-	-	-
23. INSH-M1	South east	300	AD1953	AD1999																						5.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
24. INSH-M2	South east	300	AD1958	AD1999																							-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
25. ABED-9	South east	300	AD1882	AD2000																								-	-	-	-	-	-	-	-	-	-	-	-	-	-
26. CFG-13	South east	270	AD1880	AD1979																									6.4	4.8	5.1	6.4	5.5	3.6	5.4	4.3	7.4	4.6	-	4.5	4.8
27. CFF-11	South east	280	AD1880	AD1979																										5.4	5.4	7.4	7.7	4.5	5.8	4.7	7.0	3.9	-	-	-
28. CFE-9	South east	400	AD1880	AD1979																											9.1	10.9	7.5	-	8.0	8.3	8.9	6.6	-	-	-
29. CFD-11	South east	450	AD1880	AD1979																												11.4	9.1	4.2	5.9	6.0	7.2	5.1	-	-	3.6
30. CFA-15	South east	500	AD1880	AD1979																													15.8	5.4	9.3	7.9	10.1	4.7	-	-	-
31. CFB-10	South east	550	AD1880	AD1979																														9.3	6.4	7.1	8.2	4.1	-	-	-
32. CFC-3	South east	600	AD1880	AD1979																															-	-	-	-	-	-	-
33. GLNDERRY	South east	400?	AD1773	AD1978																																12.6	13.4	4.5	-	-	-
34. INVEREY	South east	500	AD1706	AD1976																																	11.9	-	-	-	-
35. BALLOCHB	South east	380	AD1712	AD1978																																		4.5	-	4.2	3.9
37. DIMMIE	South east	200	AD1828	AD1976																																			-	-	-
38. LAPLAND			310BC	AD1993																																				-	-
39. NORW013			AD1781	AD1981																																					8.4
40. NORW014			AD1605	AD1981																																					

KEY: \ = overlap < 15 years, - = t-values less than 3.50, red = chronologies with an EPS >0.85

🟨 = samples from peat 🟧 = south east (SE) mineral substrate group 🟦 = north west (NW) mineral substrate group ⬜ = Non-Scottish reference chornologies

3.1.1 Abernethy

Abernethy is located some 10 km north-east of Aviemore (Figure 25), to the north of the Cairngorm massif, within the Spey valley, in the eastern Highlands of Scotland (Figure 3 and Figure 25). The mires sampled were at an altitude of just over 220 m in the north and north-western part of the reserve. Numerous bogs support a sparse canopy of stunted pine trees with flat-topped crowns and twisted stems and branches. There are also some clear examples of former peat cuttings, and dense and vigorous growth of pine on some of the drier banks of the aerated peat. Anderson and Harding (2002) suggest that trees from the cutover area at the north end of the bog indicate that peat cutting began at least 150 years ago and at least part of the present face was probably cut about 130 years ago. It was also thought peat cutting activity on the north-eastern part of the bog might have gradually dried the surface of the main plateau. McVean (1963a) identifies that well-drained ridges and flat areas were clear felled during the Second World War and regeneration failed almost completely, while the boggy hollows were untouched. McVean, also states at the pole stage trees may show an annual height increment of 30-40 cm, which is only a little short of that exhibited on the most favourable ground.

Increment cores were taken from this site in October 2000, as part of a study of the age structure of Scots pine on dominated bog woodland (Anderson and Harding 2002). A single increment core aimed to pass through the pith and to the far side of the tree was taken in a south/north orientation, 20 to 30 cm above the ground. The precise location of each sample was not known, but the sample numbering order is thought to usually start from the bog edge and progress to the bog centre. The cores collected were kindly made available to the author by the Forestry Commission and generally those containing over 40 rings were selected for dendrochronological analysis. New sample codes were assigned to the cores, but where possible the numbers correspond to the original numbers labelled on the cores by the Forestry Commission. Two fire scars had been identified in two trees in the field at site A and were deliberately targeted for coring.

3.1.1.1 Cross-matching and Stand Dynamics - site A (Transect 1)

Samples from this site were assigned the code ABEA. Sixteen sequences were measured from this site and cross-matched with a mean *t*-value of 3.70. These were used to establish a 203 year long mean chronology called ABEA-16, which ranged from 1798 to 2000. The 16 trees samples ranged from 140-220 years of age, with a mean age 177 years (SD = 29).

The earliest tree sampled from the site germinated *c.*1780. Between 1787 and AD 1850 eleven trees germinated at a mean rate of one every 7 years. In *c.*1855 four trees germinated. A possible grazing scar in 1816 is recorded in sample ABEA02. Fire scars are identified to have occurred in *c.*1887 and AD 1920 in samples ABEA05 and ABEA12 respectively. The season that these events occurred was indeterminable, due to the narrowness of the rings.

3.1.1.2 Cross-matching and Stand dynamics - site B (Tore Hill Bog)

Six samples from this site were measured and assigned the code ABEB. Five samples originated from trees growing on bog, and one sample (ABEB08) taken from a tree growing on cut-over bog cross-matched well together (with a mean *t*-value of 4.26) and were combined to establish a 307 year chronology called ABEB-6, which ranged from 1694 to 2000.

The earliest tree sampled from the site germinated *c.* 1663. There is then a gap of 165 years before the next germination. For the purposes of mean age, this oldest tree was treated as an outlier. The remaining five trees sampled have a mean age 121 year (SD = 20) and germinated between *c*. 1828 and *c*. 1884 at a mean rate of one every 14 years.

3.1.1.3 Cross-matching and Stand dynamics - site C (Transect 3)

This sampling transect did not follow a gradient from a peat cutting face to the bog centre. Samples from this site were assigned the code ABEC. Twenty one of the twenty two sequences measured were cross-matched (with a mean *t*-value of 3.61) to establish a 163 year long mean chronology, ranging from 1838 to 2000 which was called ABEC-21. The 21 trees samples ranged from 96-173 years of age, with a mean age 148 years (SD = 20).

The earliest tree sampled from the site was identified to have germinated *c*. 1827. A group of twelve trees with a range of germination dates of just 12 years and a mean age of 160 years (SD = 5) are all thought to have germinated *c*. 1833. Between 1852 and 1904 eight trees germinated at a mean rate of one every 7 years. Neither of the fire scares in *c*. 1887 or 1920 fires identified in Transect 1 were identified in the samples from site C; however three samples became so narrow that they could not be reliably measured at 1920.

3.1.1.4 Cross-matching and Stand dynamics - site D (Mineral substrate)

Ten sequences from this site were assigned the site code ABED. Nine sequences cross-matched (with a mean *t*-value of 3.18) to establish a 119 year mean, ranging from 1882 to 2000 called ABED-9.

The earliest tree sampled from the site germinated *c*. 1871, and was 129 years of age. There is then a gap of 55 years until what appears to be a phase of germination of six trees in *c*. 1926. The germination dates of these six trees ranges by just 9 years, and they have a mean age of 70 years (SD = 20). The two remaining trees are indicated to have germinated in 1939 and 1944. Only one tree extends back to the fire scars identified from Transect 1 which occurred in *c*. 1887 and 1920. Interestingly this tree has very narrow rings in 1920 and 1921. Comparing the growth rates for the mean site chronology over periods of 20 years prior to and after the 1920 fire shows an 85% increase in growth.

3.1.2 Achanalt

The site at Achanalt lies at the base of the northern slope of the long Strath Bran valley, some 25 km west of Dingwall. This compartment of a Scots pine plantation is located just north of the A832, a little east of the Strathbran lodge (Figure 26). The compartment had recently been felled, as part of the commercial forestry operations (Figure 27). Field walking the site located sections that had been discarded during felling operations and that were suitable for dendrochronological analysis. Nearby (NGR: NH 2177 6086) a pine was observed to have been windthrown by a south-west wind (Figure 28).

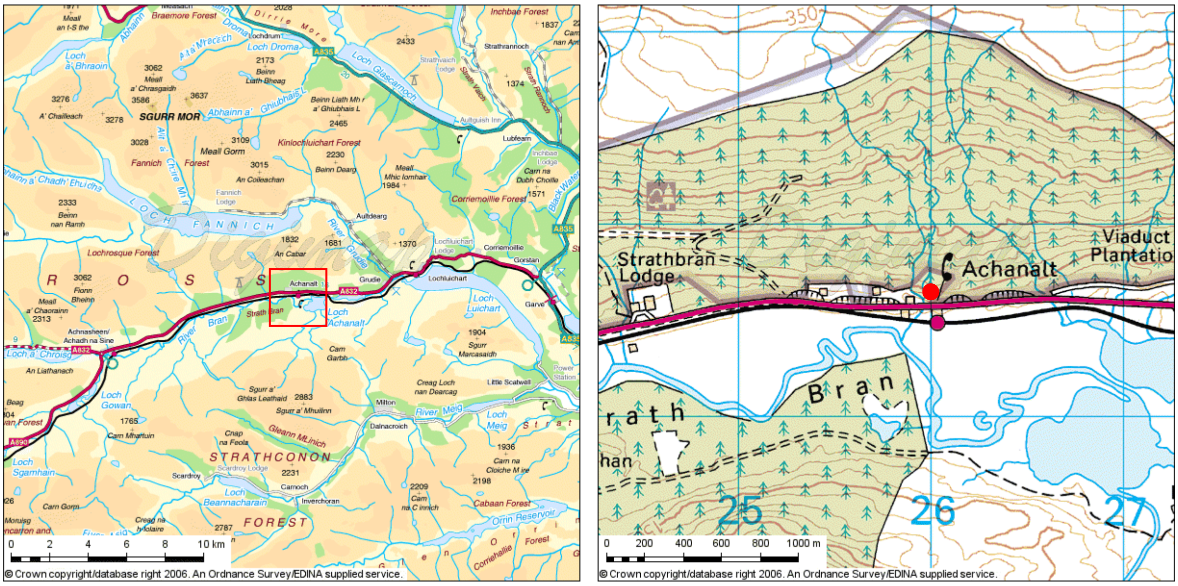


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Figure 26: Achanalt area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

Figure 27: Commercial forestry of Scots pine at Achanalt. Photograph by: A. K. Moir, 2005.

Figure 28: A Scots pine tree at Achanalt, which has been windthrown by a south-west wind. Photograph by: A. K. Moir, 2005.

In August 2005, seven samples were collected from a clear felled area at Achanalt. The samples were part disk sections that had been discarded on the site as part of the felling operation. The site appeared to have been quite recently felled, but precisely when was unknown. The surrounding trees were of straight form in relatively close habitat. The sections all came from heights of around 0.1 m. One tree (not sampled) was identified to have a 15 cm probable fire scar to the south-west (Figure 29). Although the exact location of each sample was not recorded, the sections were all orientated by matching them to their corresponding stump which remained *in situ*. The tree-rings in many of the cut stumps could be clearly distinguished, indicating a common north-east skew to the growth of trees at this site (Figure 29 and Figure 30).

Figure 29: North-east skewed growth commonly identified in the stumps at Achanalt (north is to the right, the point of the pen marks the pith). Photograph by: A. K. Moir, 2005.

Figure 30: North-east skewed growth in sample ACHA04 (north is to the right, the point of the pen marks the pith). Photograph by: A. K. Moir, 2005.

3.1.2.1 Cross-matching and Stand dynamics

All seven sections were found to cross-match with a mean *t*-value of 4.51. These were used to form a 112 year long chronology named ACHA-07, which ranged from 1893 to 2004. The mean age of the samples was 116-years (SD = 0.76), and this together with a range of only two years, clearly identified an even age stand of trees. No early common reduction in growth was identified in the early tree rings which could identify a date for planting, therefore the trees were thought to have probably germinated in *c*. 1887. The trees were felled in 2004.

Competition between the trees is perhaps responsible for the medium-frequency fluctuations (10 to 20 year) of ring width. The fluctuations are frequently out-of-phase between trees and highly stochastic. The yearly variations in ring width are dominated by these low and medium frequency fluctuations. The reasonable cross-matching between trees indicates a common signal that is strongly contaminated possibly by competition effects in the stand, or possibly by the effects of wind damage.

3.1.3 Beinn Eighe

The Beinn Eighe National Nature Reserve extends to the west of Kinlochewe, which in turn lies 25 km inland from the west coast of Scotland (Figure 25). The Scots pine trees were sampled from Coille na Glas Leitire woodland, which is in the reserve alongside Loch Maree, but lays some 12 km north-west of Kinlochewe. The woodland at Beinn Eighe is scattered and of variable canopy structure and shows a mixed range of age groups. The diversity of Atlantic bryophytes is a major feature of the site (www.jncc.gov.uk). The samples were taken as part of a BSc thesis (Barlow, 1990) and cored at breast height. The original samples were not available; however raw data are listed in the thesis and were digitized using the original sample identification labels. Five series labelled B originated from a fairly closed canopy stand of tall straight-formed trees. Seven, series labelled C originated from an area of scattered pine, experiencing more waterlogged conditions, and where the trees appeared to be restricted to slightly higher ground. Five series labelled D originated from scattered pine growing on a steep slope. A single disk section had been collected from nearby the site by Eoghain Maclean (Scottish National Heritage) and was labelled BNAA01 and included in this analysis.

3.1.3.1 Cross-matching and stand dynamics

Series B27, C8, D6, and D10 were edited to resolve problems of missing rings which became apparent during the cross-matching process. Series B1, B2, B26, B27, B28, C6, D10, D3, D6 and D9 cross-matched with a mean *t*-value of 3.60. These were used to establish a mean site chronology named BNAA-10, which ranged from 1809 to 1989. Six series from site C and one series from site D remained undated.

The earliest tree sampled from the site germinated *c*. 1793. The germination dates of six trees ranges by just 8 years, with a mean age of 176 years (SD = 4). Allowing for a lag in growth for the tree to reach the height of sampling, all six trees are thought likely to have germinated *c*. 1809. After this probably single phase of germination, the other three trees dated from this site germinate on average every 18 years. Plots of the tree-ring series show many 10 to 30 year fluctuations which are out-of-phase between trees. Sample BNAA01 did not cross-match with the other Beinn Eighe samples, but cross-matched with *t*-values of 5.08 and 5.80 againsts the mean site chronologies for Loch Maree and Shieldag, respectively, and was identified to be 158 years old and felled in the winter of 1996.

3.1.4 Borgie Forest

Borgie Forest lies 8 km south-east of the town of Tongue, 10 km inland of the north coast of Scotland (Figure 31). The site is located at the base of an eastern slope of the north-south aligned Borgie river valley. This Forestry Commission site, in the district of Dornoch, straddles the River Borgie. The site was located using a Forestry Commission stock map titled: Block 15, Borgie N, which identifies that the area was planted between 1951 and 1965, predominantly with Scots, Sitka spruce and Lodgepole pine. One area of windthrown trees located on the south-west edge of the forest was annotated on the map. Extensive blanket peat borders the forest to the west. Numerous hut circles and scheduled monuments suggest that the area has long been occupied.

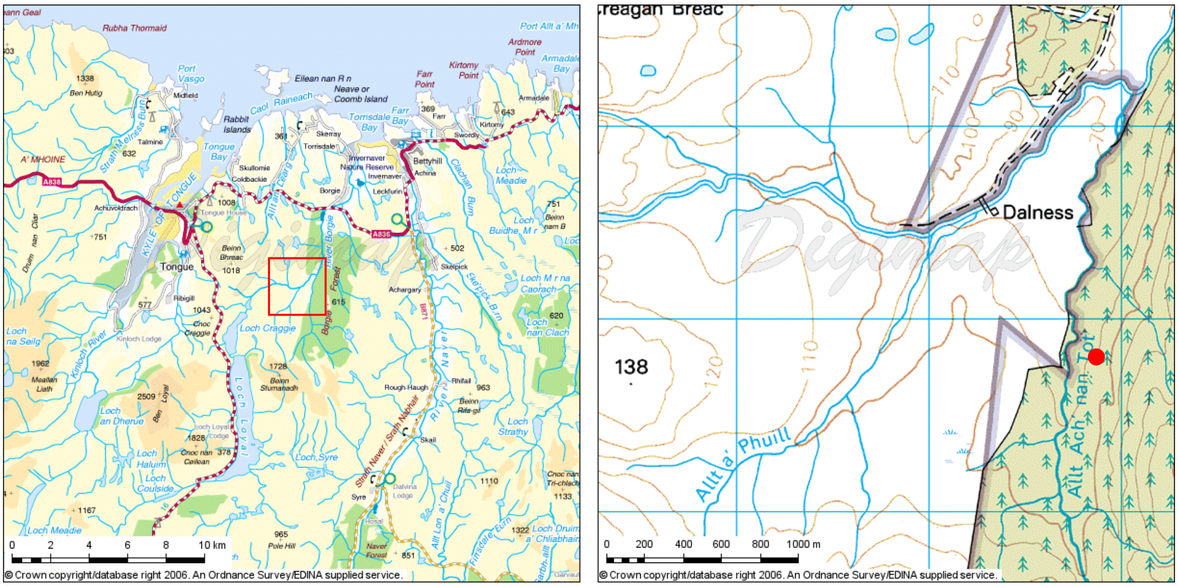

Figure 31: Borgie Forest area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

A small stand of Scots pine planted in 1951 was identified for sampling. The trees which were planted in rows had tall straight trunks and were surrounded by dense stands of Sitka spruce (Figure 32 and Figure 33).

3.1.4.1 Cross-matching and stand dynamics

In August 2005, ten cores were taken at a height of 1.3 m from Scots pine trees spread over a 30 metre area. Nine cores were found to cross-match with a mean *t*-value of 3.58 to form a 42 year long chronology, ranged from 1964 to 2005, which was named BODG-09. The germination dates of nine trees ranges by just 7 years, with a mean age of 47 years (SD = 2), reiterating they form even age stand of trees. Allowing for a lag in growth for the trees to reach the height of sampling, all nine trees are indicated to have germinated *c.* 1954. Six of the trees show a growth reduction in 1976, and thereafter the growth rate of all the trees progressively reduced.

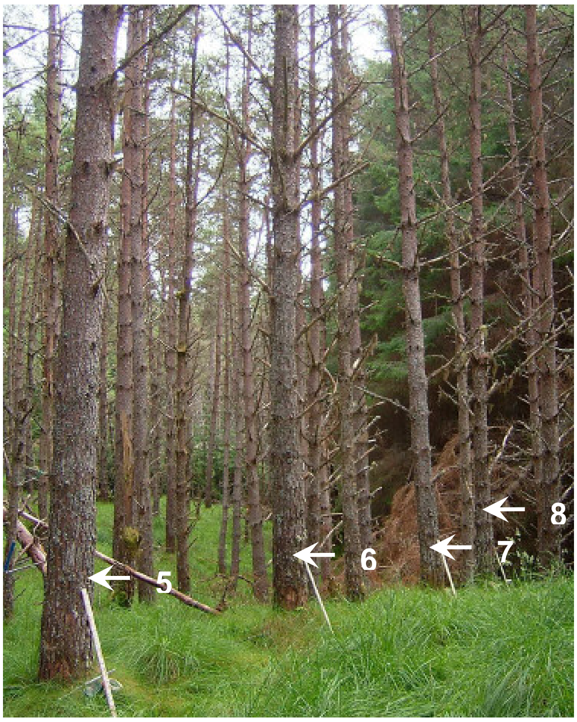

Figure 32: Borgie Forest samples BODG05 to BODG08, the trees are of straight trunk form and foliage restricted to the top. Photograph by: A. K. Moir, 2005.

Figure 33: A Scots pine tree in the Borgie Forest which has experienced windsnap by a south-west wind, a compartment of Sitka spruce are seen in the background. Photograph by: A. K. Moir, 2005.

3.1.5 Eilean Sùbhainn

Eilean Sùbhainn is the largest island in Loch Maree. It is located some 10 km south-east of Poolewe a town which lies on the west coast of Scotland (Figure 34). The island lies in the middle of the 20 km long loch which runs north-west to south-east and is bounded by mountains over 600 m on either side. Together with the other islands, this is considered to support one of the least-disturbed remnants of native pinewood in Scotland (www.jncc.gov.uk). In the wettest areas within the woodland there are small-scale examples of 91D0 Bog woodland. Permission to take single cores from up to forty Scots pines trees from the island was granted by Scottish National Heritage. Two conditions of coring at this site were that the corer was disinfected between coring each tree and that all bore holes were plugged. Cork was used to plug core holes.

A valleyside mire which extended from a crown in the south, down to a loch in the north was primarily identified for sampling. Seedlings growing on the mire were common, but few trees greater than 40 cm in height were observed. The few larger trees were stunted and tended to be restricted to the margins of the mire. Charred trunks and burnt undergrowth indicated that some of the trees at the margins of crown had been recently affected by fire. The down slope margin of the mire was rocky and ferns grew in places. The trees growing on the down slope margin were generally much larger, but few grew with straight trunks.

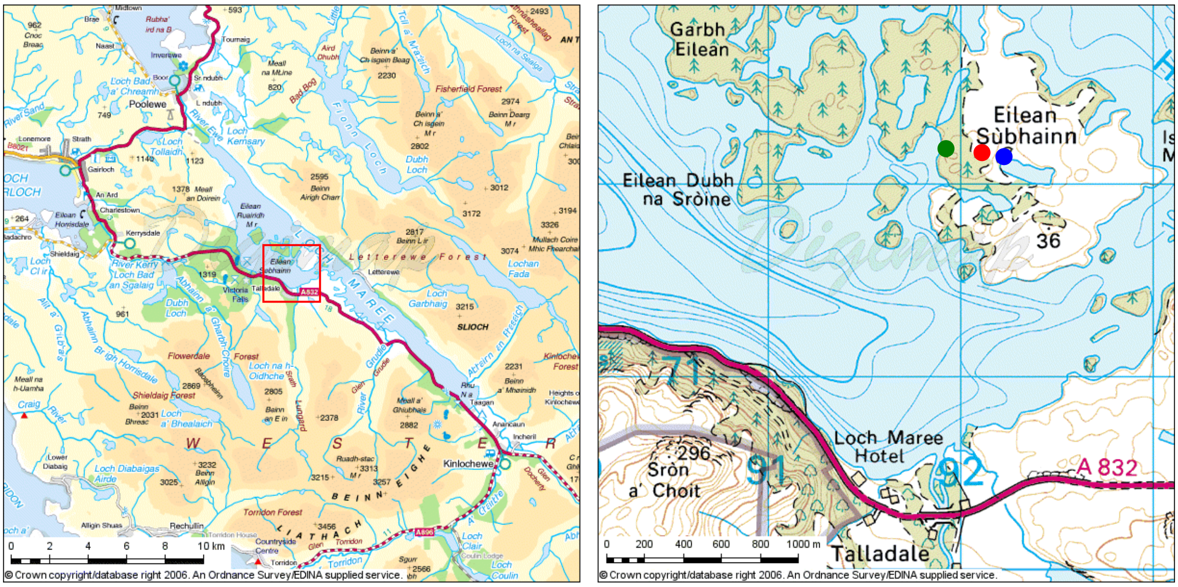

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Figure 34: Eilean Sùbhainn area and site location maps.
Red square = area enlarged in map on the right. Red dot = location of site A, Blue dot = location of site B and Green dot = location of site C.

Figure 35: Tree ESBE05 growing on the mire crown, the straight trunk above the main branch is dead. Photograph by: A. K. Moir, 2005.

Figure 36: Tree ESBE10 growing on the mire crown, with a straight trunk but stunted form. Photograph by: A. K. Moir, 2005.

In view of the difference of form between the trees growing at the crown (Figure 35 and Figure 36) and those growing on the down slope margin of the mire (Figure 37 and Figure 38), it was decided to sample about 12 trees from each location. A third sampling area of trees growing on mineral soil was then selected nearer to the shore to acts as a comparison for the two mire growth sites (Figure 39 and Figure 40). The mineral site was located on the shore of the loch and the most exposed of the 3 sites. All sampling was conducted in August 2005.

3.1.5.1 Cross-matching and stand dynamics – Site A (Mire crown)

Fourteen core samples were taken from the mire crown site. Samples from this site were assigned the code ESBE. The cores were taken as close to ground level as possible, generally from a height of 0.25 m. Nine cores were found to cross-match with a mean *t*-value of 3.83 and used to form a 137 year chronology named ESBE-09, which ranged from 1869 to 2005.

The mean age of the samples, 101-years (SD = 33.39) indicates a range of tree ages within the stand of trees sampled; no special pattern of germination was identified. The earliest tree germinated in c. 1858, and was 147 years of age. The sampled trees then germinated on average one every 6 years until c. 1890 when there is a gap of 32 years without germination. No pattern of germination was identified.

Figure 37: Tree ESDB07 growing near the bottom of the down slope margin of the mire, the loch margin is visible in the background. Photograph by: A. K. Moir, 2005.

Figure 38: Tree ESDB13 growing near the start of the down slope margin of the mire. Photograph by: A. K. Moir, 2005.

3.1.5.2 Cross-matching and stand dynamics – Site B (Mire down slope margin)

Thirteen core samples were taken from the mire down slope margin. Samples from this site were assigned the code ESDB. The cores were taken as close to ground level as possible, generally from a height of 0.25m. Twelve cores were found to cross-match with a mean *t*-

value of 4.55 and used to form a 216 year long chronology named ESDB-12, which ranged from 1790 to 2005.

The mean age of the samples, 164-years (SD = 45.23) indicates a range of tree ages within the stand; no special pattern of germination was identified. The earliest tree germinated in *c*.1779. The trees sampled then germinated on average one every 10 years until *c*.1871 when there is a gap of 35 years apparently without germination. The oldest trees germinated near the centre of the bog. After 1940 all the trees show a downturn in growth and the rings from trees ESDB02, ESDB06 and ESDB08 become too narrow to reliably measure from 1979, 1974 and 1977, respectively (see Figure 118). Interestingly the two earliest samples, which are located at the centre of the site, also become too narrow to measure at this time.

Figure 39: Trees ESDG05 (foreground) and ESDG01 (the tree windthrown by a westerly wind in the background). Photograph by: A. K. Moir, 2005.

Figure 40: Tree ESDG06 growing on mineral substrate but close to the loch margin. Photograph by: A. K. Moir, 2005.

3.1.5.3 Cross-matching and stand dynamics – Site C (Mineral substrate)

Thirteen core samples were taken from a height of 1.3m. All thirteen cores were found to cross-match with a mean *t*-value of 4.21 and used to form a 169 year long chronology named ESDG-13, which ranged from 1837 to 2005. The mean age of the samples, 122-years (SD = 38.46) identifies a range of tree ages within the stand; no special pattern of germination was identified. The earliest tree sampled germinated in *c*. 1818. The trees then germinated on average one every 6 years until *c*. 1880 when there is a gap of 74 years apparently without germination. Almost all the samples show a growth reduction from 1910. A total of seven trees become too narrow to reliably measure to bark, this occurs after 1938, 1941 and 1945 in the earliest three trees affected.

In summary, Scots pine has been growing on the down slope margin of the bog at Eilean Sùbhainn since *c*. 1779, and trees spread onto the crown of this bog *c*. 1858. The samples indicate that since these first occupations, at least once every decade pine has germinated at both sites until the 1870s when there is an apparent about 30 year absence of germination (Figure 107). Only five trees sampled germinated after 1910. The reduction in growth normally related to age is absent from these trees.

3.1.6 Inshriach Bog

Inshriach Forest is located inland at the western foot of the Cairngorm Mountains, some 12 km south-west of Aviemore (Figure 25). The following description of the site is drawn from Anderson and Harding (2002). Most of the trees are markedly stunted. The presence of an eroded peat face besides the bog, and the peat depth of only 5-75 cm indicate that the bog had been entirely cut-over. The pine trees all appear to have developed recently on a secondary surface, probably seeded from a forest adjacent to the bog, which was planted around 60 years ago. Both the height and diameter growth rates of the pines are slow (1-4 mm diameter per year in transect 1 compared with 3-5 mm per year on the adjacent dry ground) and apparently constrained by the soil conditions.

In August 1999 increment cores were taken, as part of a study of the age structure of Scots pine on dominated bog woodland (Anderson and Harding 2002). A single increment core aimed to pass through the pith and to the far side of the tree was taken in a south/north orientation, 20 to 30 cm above the ground. The sampling transect followed along the gradient from a peat cutting face to the bog centre. The samples were taken from over one approximate 40 m transect which ran from shallow peat (about 0.5 m) to deeper peat (1.1 m for T1; 3.1 m for T2). These core samples were kindly made available to the author by the Forestry Commission and those containing over 40 rings measured for dendrochronological analysis.

3.1.6.1 Cross-matching and stand dynamics – site A (Cutover bog)

Of the seven sequences of sufficient length to measure, only three sequences could be cross-matched with a mean *t*-value of 2.66 and used to form a 47 year long chronology called INSH-M1, which ranged from 1953 to 1999. Although the sample is small, the mean age of the samples, (55-years, SD = 2.65) is consistent with the ring counts of seven other sequences which could not be cross-matched, and suggests an even age stand of trees that germinated in *c*. 1942. One sample which could not be cross-matched contained *c*. 93 rings, indicating that it had probably been growing on the site since 1906. All three trees show progressive growth reduction from 1978.

3.1.6.2 Cross-matching and stand dynamics – site B (Mineral substrate)

Of the six sequences of sufficient length to measure, only two sequences could be cross-matched with a *t*-value of 4.0 and used to form a 42 year long chronology called INSH-M2, which ranged from 1958 to 1999. Both trees appear to have germinated in c. 1947 which is consistent with the ring counts of the four other sequences which could not be cross-matched. Both sequences show progressive growth reduction from 1986.

3.1.7 Monadh Mor

Monadh Mor is located 12 km north-west of Inverness, on the east coast of Scotland (Figure 25). The following description of the site is drawn from Anderson and Harding (2002). The area is a complex area of ridges and hollows resulting from glacial deposition. Many of the areas have become filled with peat and swamp, though larger depressions contain open water. The ridges are free-draining and are largely wooded with Scots pine and birch *Betula* spp, while the more extensive hollows support *Sphagnum* bog on which stunted pine is abundant. The pine-bog relationship appears to be stable and the pines are still growing. The site represents one of the largest areas of bog woodland in a single location in the UK, with an estimated 75 hectares of the habitat.

Increment cores were taken from this site in June 2000, by Anderson and Harding (2002). A single increment core aimed to pass through the pith and to the far side of the tree was taken in a south/north orientation, 20 to 30 cm above the ground. The cores were kindly made available to the author by the Forestry Commission and those containing over 40 rings measured for dendrochronological analysis. The samples were taken from over two approximate 30 m transects with similar vegetation (*Eriophorum vaginatum*) which ran from shallow peat (about 0.5 m) to deeper peat (1.1 m for T1; 3.1 m for T2). The original core sample mounts did not identify from which transect cores originated.

3.1.7.1 Cross-matching and stand dynamics

Six sequences were cross-matched with a mean *t*-value of 3.33 and used to form a 94 year long chronology called MONH-M1, which ranged from 1906 to 1999. The earliest tree germinated *c*. 1890. A mean age of 96-years (SD = 2.30, range 5 years) indicates that the other five trees are all likely to have germinated in *c*. 1901. All trees show a sharp growth reduction in 1961 which then progressively increases.

Four other sequence cross-matched with a mean *t*-value of 3.82 and were used to form a 66 year long chronology called MONM-M2, which ranged from 1934 to 1999. A mean age of 72-years, (SD = 4.50, range 10 years) is taken to indicate that all four trees are likely to have germinated in *c*.1923. This phase of germination is consistent with the ring counts of the two other sequences which could not be cross-matched. All trees show a sharp growth reduction in 1961 which lasts for less than 10 years before recovery and progressive growth increase until 1990 when another sharp decrease occurs.

3.1.8 Pitmaduthy Moss

Pitmaduthy Moss is situated 12 km south of Dornoch, a town located on the east coast of Scotland (Figure 25). The following description of the site is drawn from Anderson and Harding (2002). This bog woodland site has, unusually, developed under relatively dry climatic conditions. The communities, which have strong affinities with Scandinavian bogs, are a complex of poor fen and bog. The Moss consists of a system of pools in a shallow hollow bounded by low ridges. Scattered stunted Scots pine occurs on the slightly drier areas within the hollow, with a characteristic slow growth pattern and in a stable relationship with the bog surface. The trees become more abundant and attain greater size on the drier ridges. The sampling transect followed along the gradient from a peat cutting face to the bog centre. Air photographs show that all the large trees disappeared from the western part of Pitmaduthy Moss (this includes the transect of woodland bog sampled, but not the samples from the mineral substrate) between 1946 and 1959, presumably in a timber harvesting or bog clearing operation. Peat stratigraphy shows evidence of truncation in the peat layers, suggesting a history of peat-cutting at this site.

Increment cores were taken from this site in June 2000, by Anderson and Harding (2002). A single increment core aimed to pass through the pith and to the far side of the tree was taken in a south/north orientation, 20 to 30 cm above the ground. The cores were kindly made available to the author by the Forestry Commission and those containing over 40 rings measured for dendrochronological analysis. The peat samples were taken from over an approximate 30 m transect which ran from the bog edge towards its centre.

3.1.8.1 Cross-matching and stand dynamics (peat substrate)

Twelve sequences cross-matched with a mean *t*-value of 5.68. These were used to establish a 125 year long chronology called PITM-M1, which ranged from 1875-1999. The earliest tree germinated *c*. 1863, seven trees with a mean age of 116 year (SD = 3.67, range 7 years) indicates they probably germinated *c*. 1880.

3.1.8.2 *Cross-matching and stand dynamics (mineral substrate)*

Six sequences were cross-matched with a mean *t*-value of 4.44. These were used to establish a 62 year long chronology called PITM-M2, which ranged from 1938-1999. The earliest tree germinated *c*. 1863, seven trees with a mean age of 116 year (SD = 3.67, range 7 years) indicates they probably germinated *c*. 1880.

3.1.9 Strathnaver Forest

The Strathnaver Forest lies 20 km south south-east of the town of Tongue, 22 km inland of the north coast of Scotland (Figure 41). This Forestry Commission site, in the district of Dornoch, borders each side of the River Naver. The site was located using a Forestry Commission stock map titled: Blks 20 & 21, Syre & Rosal (N), this map identified that the area had been planted between 1958 to 1965, with a mixture of mainly Scots pine, Sika pine, and Lodgepole pine, but with some Japanese/Hybrid Larch. Numerous hut circles suggest that the area has long been occupied. Most of the area surrounding the plantation consists of treeless blanket bog, with areas of open water. The valley of the river Naver is generally SW/NE orientated, the site located on the southeast bank of the river. Ten areas of windthrown trees were annotated on the map as "windblown" on the Forestry Commission stock map. Five areas were located on the south-west edge, two on the north-east edge, and one on the north-west edge. Two instances were in the interior of the forest, but located on what appeared to be the more exposed east bank of the river.

The earliest planted area of Scots pine in the area was 1959, but the area selected for sampling was one affected by windthrown trees. The area was located on the east bank of the river and close to the east forest access road. Scots pine and Lodgepole pine in the area were planted in 1962.

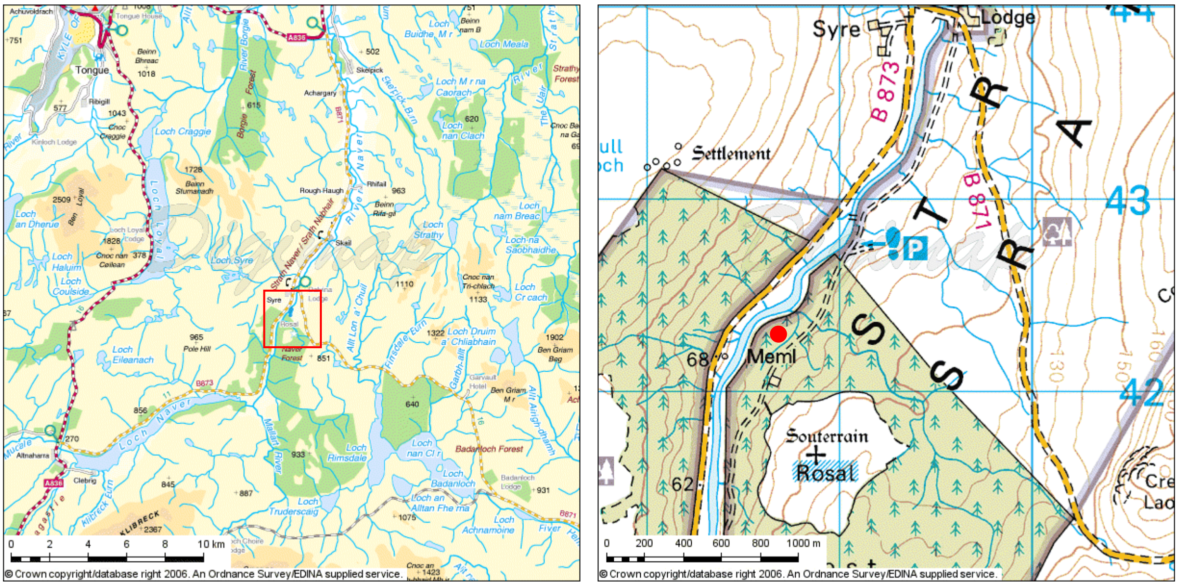

Figure 41: Strathnaver Forest area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

Three sub-areas of trees were sampled from this site. In the first area (A) a small area of shallow drained blanket peat with both Scots pine and Lodgepole pine, had been devastated, leaving only a few trees standing at the periphery (Figure 42 and Figure 43). The vast majority of these trees had been windthrown to the north-east, indicating a south-west wind. A few trees had been wind snapped. Scots pine left standing had tall straight trunks and foliage was restricted to the very tops of the trees.

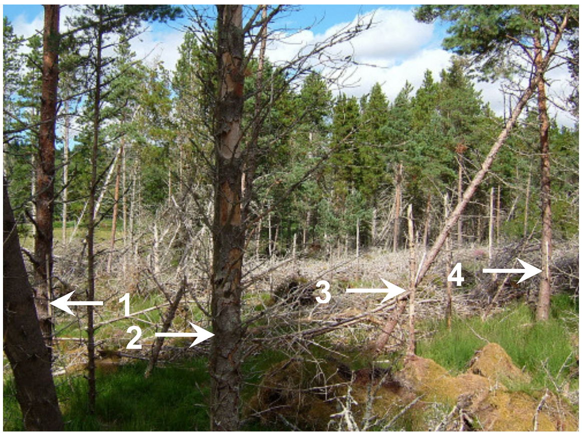

Figure 42: Trees STPE01 to STPE04 from an area of predominantly windthrown and wind snapped by a south-west wind. Photograph by: A. K. Moir, 2005.

Figure 43: Trees STPE08 and STPE09 with straight form trunks. The trees in the background have been windthrown by a south-west wind. Photograph by: A. K. Moir, 2005.

Area B was located on the exposed western edge of the forest, boarding the Naver river (Figure 44 and Figure 45). A number of dead trees were observed along the edge of the forest. These Scots pine trees had some foliage lower down the truck, growing mainly west presumably towards the available light.

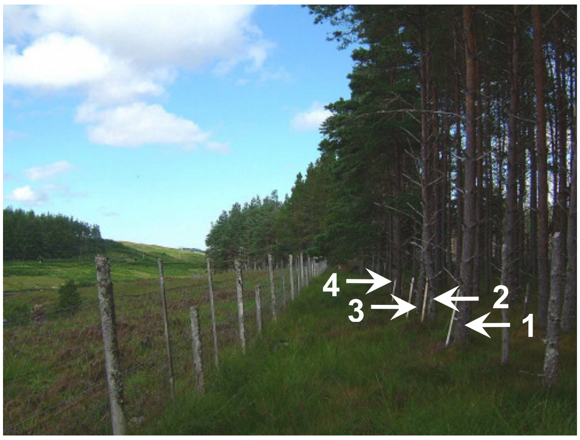

Figure 44: The river Naver runs between the west bank of trees (left) and the east bank of trees (right), from which trees STWB01 to STWB04 were sampled. Photograph by: A. K. Moir, 2005.

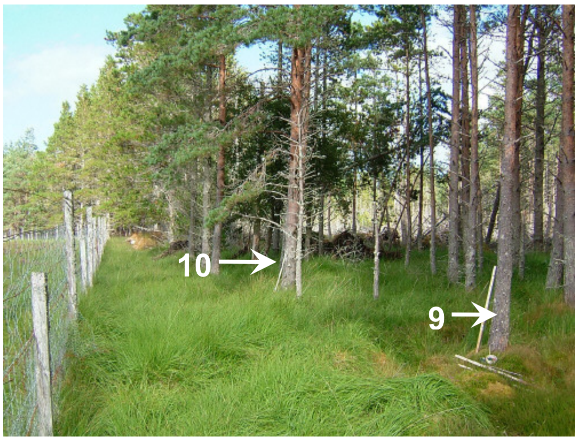

Figure 45: Trees STWB09 and STWB10, a stand of Lodgepole pine (*Pinus contorta*) starts at the end of the fence. Photograph by: A. K. Moir, 2005.

Area C (STIN) was located in the interior of a stand of Scots pine, some 20m in from the western edge which boarded the river Naver. Ten trees were sampled from this area (Figure 46 and Figure 47).

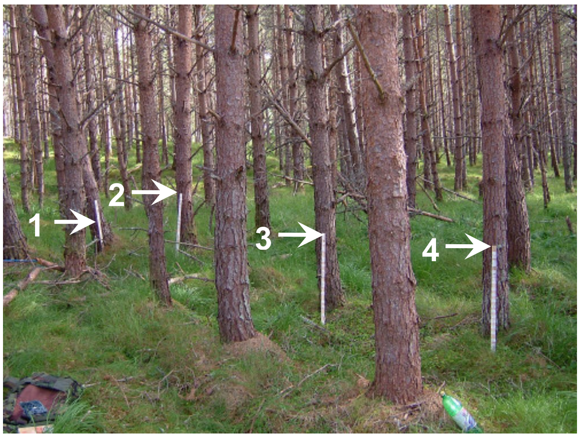

Figure 46: Trees STIN01 to STIN04, in a close stand of Scots pine. Grass can be observed growing on what was once probably blanket bog. Photograph by: A. K. Moir, 2005.

Figure 47: Trees STIN08 to STIN10, all the trees in this stand had straight trunks and foliage restricted to the tops of the trees. Photograph by: A. K. Moir, 2005.

3.1.9.1 Cross-matching and stand dynamics – Area A (blanket bog)

In August 2005, ten core samples were taken from a mean height of 1.30m. All the samples failed to cross-match together, or against reference chronologies. The mean age of the samples is 41-years (SD = 3.92). Low standard deviation indicates this is an even age stand of trees germinated in *c*.1964.

3.1.9.2 Cross-matching and stand dynamics – Area B (Forest edge)

In August 2005, ten core samples were taken from area B from a mean height of 0.69m. Six sequences cross-matched with a mean *t*-value of 4.25 and were used to form a 41 year long chronology called STWB-06, which ranged from 1965 to 2005. A mean age of 43-years, (SD = 2.48, range 6 years) indicates it likely that all six trees germinated in *c*. 1959 or soon after. This phase of germination is broadly consistent with the ring counts of the two other sequences that could not be cross-matched. A Forestry Commission map identifies this compartment to have been planted in 1962; therefore the saplings are indicated to have been at most 3 years old at planting.

3.1.9.3 Cross-matching and stand dynamics – Area C (Forest interior)

In August 2005, ten core samples were taken from area C, from a mean height of 0.80 m. Seven measured sequences cross-matched with a mean *t*-value of 3.33 and were used to form a 40 year long chronology called STIN-07, which ranged from 1966 to 2005. A mean age of 46-years, (SD = 1.46, range 4 years) is taken to indicate that all four trees are all likely to have germinated in *c*. 1957 or soon after. This phase of germination is consistent with the ring counts of the three other sequences which could not be cross-matched. As this compartment is identified by the Forestry Commission map to have been planted in 1962, this indicates that the saplings were at most 5 years old when planted.

Looking at the sequences for both the sites B and C together, overall this compartment of Scots pine reaches its maximum radial growth rate of just over 4.0 mm yr^{-1} in the 1970s before rapidly reducing to radial growth rate of 0.9 mm yr^{-1} in the 2000s. The growth of two trees also became too narrow to allow reliable measurement in this decade. All three sites are identified by the Forestry Commission map to have been planted in 1962 and it is most likely that these adjacent compartments were all planted at the same time. This suggests that trees of 3-5 years old were planted and that trees on the bog site which failed to cross-match had an average of two rings missing.

3.2 Holocene Scots pine sites

Thirteen Holocene pine chronologies from 8 of the 10 areas sampled were developed (Figure 48). In total 134 Holocene Scots pine trees were sampled, of these 20% were unmeasured, 26% unmatched and 54% were cross-matched. A summary of the Holocene pine chronologies used in this study is presented (Table 5). Of the original total, 37% cross-matched together.

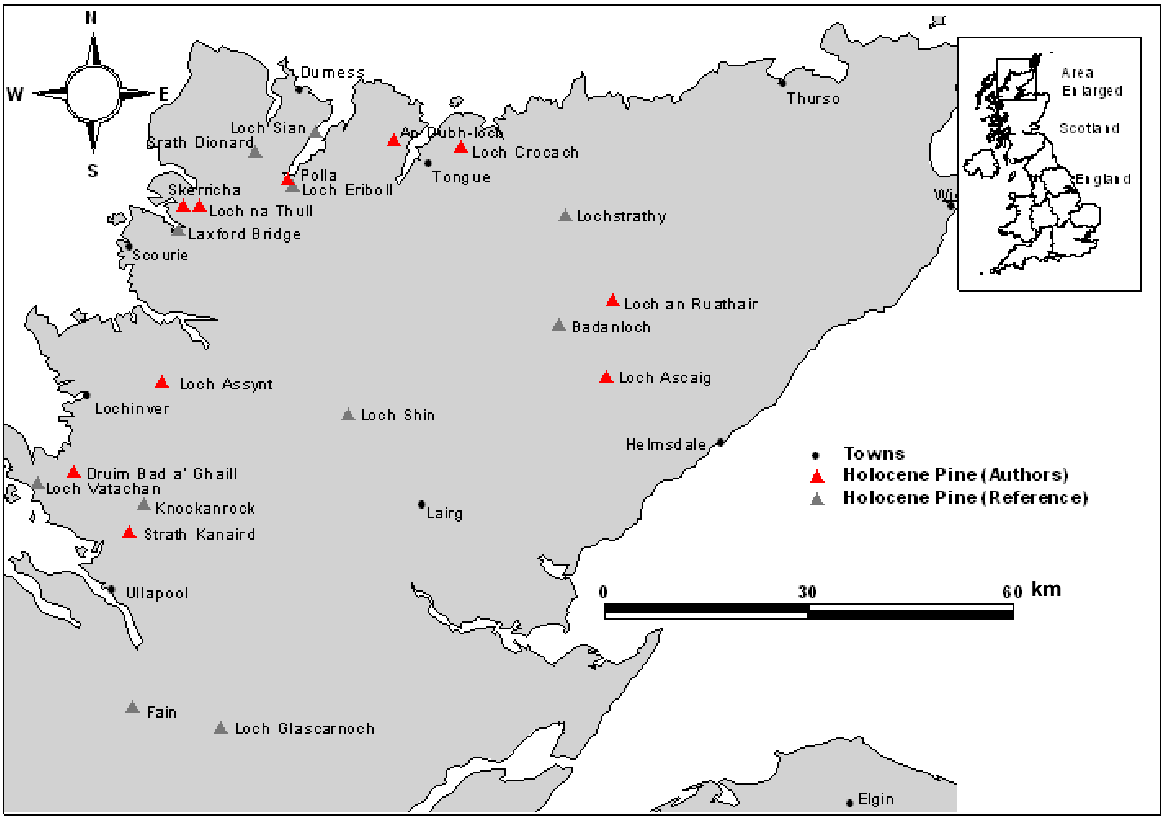

Figure 48: The location of Holocene pine sites used in this study, with the exception of Loch Farlary which lies 25 km south-west of Helmsdale.

To help the comparison of Holocene data, it is listed broadly from the north-west (NW) to the south-east (SE), but with some consideration to altitude (Table 6). The sites are generally listed in this same order throughout this study in an attempt to help highlight region patterns. However, it should be recognised that the climate the trees were exposed to during growth may have been quite different to that of present day.

Table 5: Summary table of subfossil pine sites sampled and chronologies
MR = mean ring width, MS = Mean sensitivity, AC = Auto correlation, SD = Standard deviation & underlined = estimated or taken from other published results.

Map Key	Site name	Latitude (dec. deg.)	Longitude (dec. deg.)	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 (site code)	MR	MS	AC	Mean Age	SD	Chronology Span	Chronology length (yr.)	Oldest tree at site (yr.)
H1	An Dubh-loch	58.51	-4.50	140	Valleyside mire	2.50	0.10	3	3	100%	5.24	1	DUBH-3	0.98	0.25	0.75	93	9	105-197	93	98
H2	Druim Bad a' Ghaill	58.05	-5.27	130	Watershed mire	0.62	-0.02	15	12	88%	4.10	1	BADA-12	0.96	0.20	0.66	156	28	60-245	186	196
H2	Druim Bad a' Ghaill	58.05	-5.27	130	Watershed mire	0.52	0.10	6	6		5.12	1	BADA-B	1.35	0.21	0.90	84	29		112	140
H2	Druim Bad a' Ghaill	58.05	-5.27	130	Watershed mire	0.43	0.00	3	3		4.65	1	BADA-C	1.62	0.19	0.65	87	14		102	100
H3	Loch an Ruathair	58.30	-3.94	130	Valleyside mire	1.11	0.02	10	8	83%	3.62	3	RATH-8	0.86	0.20	0.78	191	37	61-292	232	243
H3	Loch an Ruathair	58.30	-3.94	130	Valleyside mire	0.54	-0.05	2	2		8.15	3	RATH-B	1.23	0.25	0.85	134	47		102	167
H4	Loch Ascaig	58.20	-3.95	140	Valleyside mire	0.50	0.10	5	3	75%	5.54	1	ASCA-3	0.86	0.18	0.82	133	58	63-246	184	199
H4	Loch Ascaig	58.20	-3.95	140	Valleyside mire	0.50	0.10	3	3		5.16	1	ASCA-B	0.54	0.20	0.82	183	56		190	223
H5	Loch Assynt	58.17	-5.06	80	Valleyside mire	1.60	0.10	8	4	50%	3.26	1	ASSA-4	0.98	0.17	0.79	231	71	44-300	257	299
H6	Loch Crocach	58.50	-4.33	100	Valleyside mire	0.50	0.10	4	0	0%		1	(CROC)				138	47			204
H7	Loch na Thull	58.41	-4.99	40	Valleyside Mire	0.53	0.04	3	0	0%		1	(THUL)				142	45			179
H8	Polla on Loch Eriboll	58.45	-4.76	10	Valleyside mire	1.11	0.23	10	6	60%	4.69	2	POLL-6	0.71	0.18	0.79	248	69	25-368	344	354
H9	Skerricha	58.41	-5.02	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
H10	Strath Kanaird	57.97	-5.12	360	Spur mire	2.09	0.14	19	13	71%	3.43	1	SMUR-13	0.91	0.16	0.80	228	72	103-410	308	338
H10	Strath Kanaird	57.97	-5.12	360	Spur mire	1.12	0.05	2	2		5.88	1	SMUR-B	1.06	0.20	0.73	223	4		221	226
HA	Badanloch	58.27	-4.07	120	Reservoir edge			54	15	28%			BADAN-ED	0.75	0.18	0.81	100		52-217	166	166
HB	Fain	57.74	-5.09	300				6		0%				0.54	0.29	0.78	184				
HC	Knockanrock	58.01	-5.09	210				2		0%											
HD	Laxford Bridge	58.37	-5.03	10	Peat cutting	0.65		12	9	75%				1.01	0.30	0.73	110				178
HE	Loch Eriboll	58.44	-4.75	10				2		0%											
HF	Loch Glascarnoch	57.72	-4.87	250	Reservoir edge	0.50		21	15	71%				0.61	0.29	0.75	154				232
HG	Loch Shin	58.14	-4.59	90	Reservoir edge	0.50		29	19	66%			SHIN-ED	0.57	0.21	0.73	115		6-189	184	184
HH	Loch Sian	58.51	-4.70	50				1		0%											215
HI	Loch Vatachan	58.03	-5.36	20	Old peat cutting	?		27	20	74%			VATCH-ED	0.96	0.24	0.73	86		41-201	161	363
HJ	Lochstrathy	58.41	-4.06	160	Forest road cutting	?		34	0	0%				0.63	0.30	0.72	60				
HK	Srath Dionard	58.48	-4.85	20	Peat erroded by river	1.00		10	5	50%				1.13	0.30	0.74	101				173
n/a	Loch Farlary	58.02	-4.08	220	Loch edge	2.50	0.00	6	2	33%			FARLY-2	0.96	0.22	0.79	131	33		154	368

Table 6: Scottish sites of Holocene Scots pine used in this study, broadly listed on a north-west to south-east transect, but with consideration to site type and altitude. Oceanicity and climate conditions are also shown (Birse 1971).

Order	Site name	Site	Latitude (dec. deg.)	Longitude (dec. deg.)	Altitude (m)	Oceanicity	Climate conditions
1	An Dubh-loch	Peat	58.51	-4.50	140	1	h2b2
2	Loch Crocach	Peat	58.50	-4.33	100	1	h2b3
3	Loch Sian	Peat	58.51	-4.70	50	1	h2b2
4	Skerricha	Peat	58.41	-5.02	40	1	h2b3
5	Loch na Thull	Peat	58.41	-4.99	40	1	h1b3
6	Srath Dionard	Peat	58.48	-4.85	20	1	h2b2
7	Laxford Bridge	Peat	58.37	-5.03	10	1	h2b3
8	Polla on Loch Eriboll	Peat	58.45	-4.76	10	1	h1b1
9	Loch Eriboll	Peat	58.44	-4.75	10	1	h1b1
10	Loch Vatachan	Peat	58.03	-5.36	20	1	h2b3
11	Druim Bad a' Ghaill	Peat	58.05	-5.27	130	1	h1b2
11	Druim Bad a' Ghaill	Peat	58.05	-5.27	130	1	h1b2
11	Druim Bad a' Ghaill	Peat	58.05	-5.27	130	1	h1b2
12	Loch Assynt	Peat	58.17	-5.06	80	2	h2b2
13	Knockanrock	Peat	58.01	-5.09	210	2	h1b2
14	Strath Kanaird	Peat	57.97	-5.12	360	1	h1b2
14	Strath Kanaird	Peat	57.97	-5.12	360	1	h1b2
15	Fain	Peat	57.74	-5.09	300	2	h1b2
16	Loch Glascarnoch	Peat	57.72	-4.87	250	2	h1b2
17	Loch Shin	Peat	58.14	-4.59	90	2	h2b2
18	Lochstrathy	Peat	58.41	-4.06	160	2	h1b2
19	Badanloch	Peat	58.27	-4.07	120	2	h2b2
20	Loch an Ruathair	Peat	58.30	-3.94	130	2	h2b2
20	Loch an Ruathair	Peat	58.30	-3.94	130	2	h2b2
21	Loch Ascaig	Peat	58.20	-3.95	140	2	h2b2
21	Loch Ascaig	Peat	58.20	-3.95	140	2	h2b2
22	Loch Farlary	Peat	58.02	-4.08	220	2	h1b1

Seven subfossil pine chronologies containing a total of forty nine individual series are cross-matched together to form a 410 year long mean chronology called WRATH-7 (Table 7).

Table 7: Cross-matching between subfossil pine mean site chronologies in the WRATH-7 and WRATH-9 reference chronologies, RY = Relative years

Filenames	Relative start year	Relative end year	ASSA-4	BADA-12	RATH-8	ASCA-3	SMUR-13	DUBH-3	VATCH-ED	BADAN-ED
POLL-6	25	368	-	3.53	-	-	4.80	-	4.03	4.67
ASSA-4	44	300		5.03	-	-	3.70	4.33	4.28	3.53
BADA-12	60	245			4.33	-	4.44	4.12	7.24	5.58
RATH-8	61	292				5.22	6.23	-	-	6.62
ASCA-3	63	246					4.63	-	-	5.51
SMUR-13	103	410						3.70	-	3.99
DUBH-3	105	197							-	3.58
VATCH-ED	41	201								3.79
BADAN-ED	52	217								

KEY: Grey = not in WRATH-7 chronology, \ = overlap < 15 years, - = t-values less than 3.50
Statistics: n = 36, min t = 0.88, max t = 7.24, mean t = 3.87 SD = 1.37

The two shortened chronologies BADAN-ED and VATCH-ED cross-match well with *t*-values of 8.27 and 5.57 respectively against the WRATH-7 chronology. These two chronologies were combined with the seven site chronologies in WRATH-7, to form a mean regional chronology called WRATH-9 (Table 7). Close visual matching between the WRATH-7 and BADAN-ED chronologies help reinforce both the correct cross-matched position and annual resolution of these sequences (Figure 49).

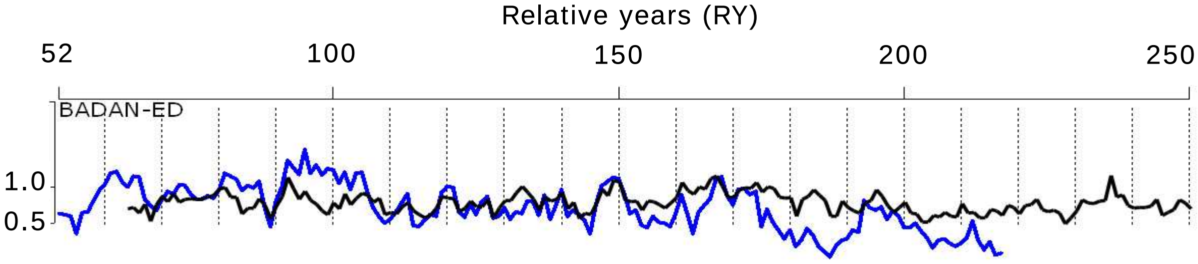

Figure 49: Plots of the tree-ring sequences BADAN-ED (blue) against a shortened section of the WRATH-7 chronology (black).
Ring width (mm) is plotted on a logarithmic scale on the y axis, using a common axis.

Attempts to cross-match and calendar date the WRATH-9 chronology were against either Holocene oak and Scots pine tree-ring chronologies. No significant, well replicated cross-matches were found for the WRATH-9 chronology against chronologies developed in Ireland (pers. comm. David Brown, Queens University Belfast 2007); England (pers. comm. Cathy Groves, Sheffield University 2007), Finland (pers comm. Samuli Helama, University of Helsinki 2007) and Germany (pers comm. Hurbert Leuschner, University of Göttingen 2008) and therefore the chronology could not be dendrochronologically dated. Nevertheless, cross-matching of the component sequences helps confirm their predominant annual resolution and as they are cross-matched relative to each other, their relative positions are quoted in relative years (RY).

3.2.1 An Dubh-loch

An Dubh-loch lies just off the A838, 5 km north-west of Tongue, 6 km south of the northern coast of Scotland (Figure 50). This lowland site (140m) is very exposed and treeless today. During site reconnaissance in September 2001, the valley side mire found at the southern end of the loch was found to contain some pine stumps. These appear to have become exposed through peat cutting. The majority of stumps contained insufficient rings, but three suitable samples were collected and the site assigned the code DUBH.

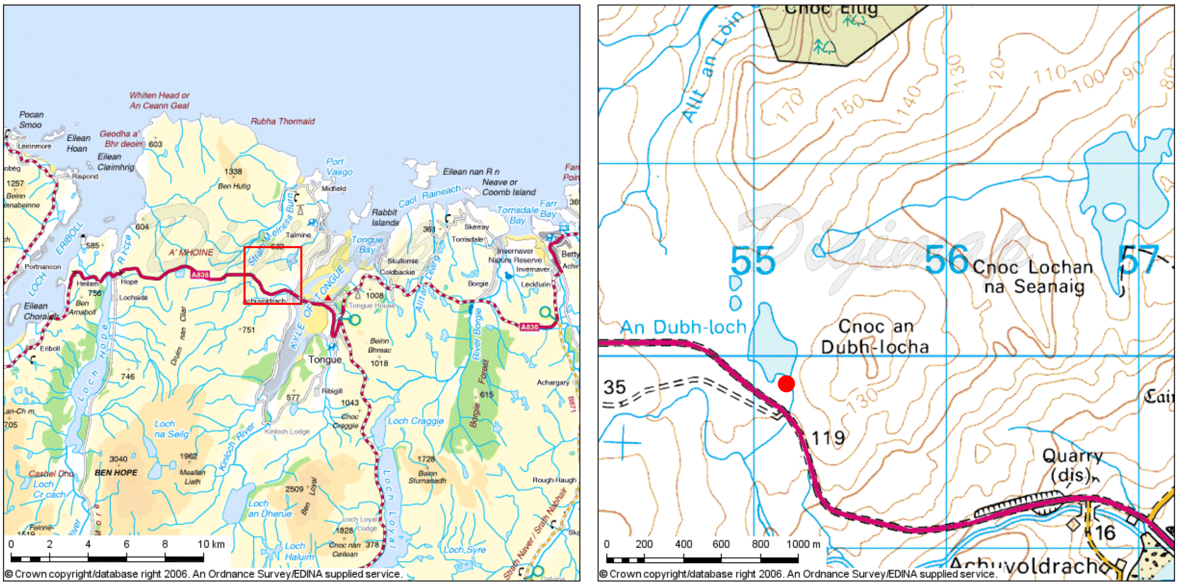

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Figure 50: An Dubh-loch area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

3.2.1.1 *Cross-matching and stand dynamics*

All three sequences collected were of sufficient length to measure. These sequences were cross-matched with a mean *t*-value of 5.24 and used to form a 93 year long chronology called DUBH-3. This chronology was found to cross-match at a relative position of years 105 to 197 against other subfossil pine site chronologies and was included in the reference chronology named WRATH-9. The three trees are identified to have germinated within a short range (between RY 95 and 111). The trees cross-matched had a mean radial growth rate of 1mm for their first 70 years of growth. Probably bark on one sample identifies the death of a tree in the RY 203. Pine appears to have grown at this site for a period of 110 years. Over the final 30 years growth, reduced to a level below 0.5 mm yr^{-1}, which was quickly followed by death.

3.2.2 Druim Bad a' Ghaill

Druim Bad a' Ghaill lies 10 km south of Lochinver, just 2 km from the west coast of Scotland (Figure 51).

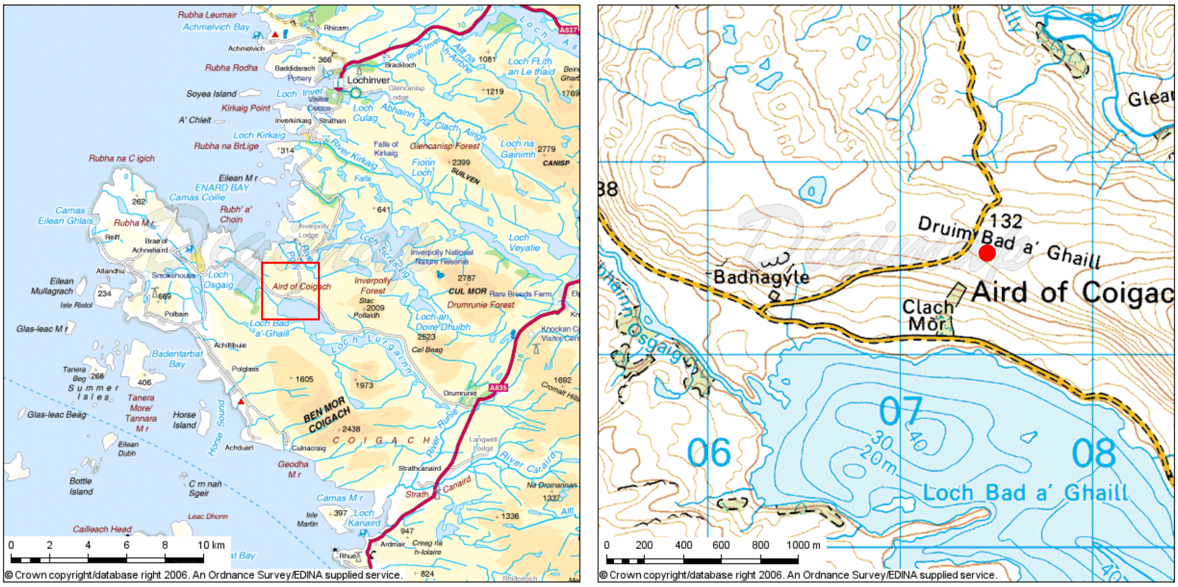

Figure 51: Druim Bad a' Ghaill area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

The site is exposed and treeless today (Figure 52). Subfossil pine stumps were exposed in a drainage ditch next to and in well developed gullies of this watershed mire (Figure 53). One layer of pine stumps was observed and there was evidence of peat cutting.

Figure 52: Druim Bad a' Ghaill watershed mire site looking north-east. Photograph by: A. K. Moir, 2004.

Figure 53: Druim Bad a' Ghaill site looking north-east, showing samples exposed by a drainage gully. Photograph by: A. K. Moir, 2004.

3.2.2.1 Cross-matching and stand dynamics

In June 2002 twenty nine samples were collected and assigned the site code BADA. Twenty four of the samples collected were of sufficient length to be measured. Twelve sequences were cross-matched with a mean *t*-value of 4.10 and used to form a 186 year long chronology called BADA-12. This chronology was found to cross-match at a relative position of years 60 to 245 against other subfossil pine site chronologies and was included in the reference chronology named WRATH-9. Six remaining sequences cross-matched with a mean *t*-value of 5.12 to form a 112 year long chronology called BADA-B, and three to form a 102 year long chronology called BADA-C. No further cross-matching using the chronologies BADA-B or BADA-C was established.

The first tree germinated at this site in RY 5, followed by the germination of seven trees at a mean rate of 1 every 7 years. Four remaining trees had a mean age of 89-years (SD = 3.65, range 8 years), indicating they were all likely to have germinated in RY 85 or soon after. Apparently coinciding with this second phase of germination, the 9th and 10th decades (RY) is one of the few periods where radial growth exceeds 1.0 mm yr^{-1}. Interestingly, three of this latter germinated group of trees are located near the centre of the sampling location, perhaps indicating the centre of the mire had become suitable for germination.

A mean of the eight peripheral trees shows a fairly constant mean radial growth rate of 0.97 mm yr^{-1} until reductions to 0.84 and 0.65 mm yr^{-1} in the 18th and 19th decades RY. The reduction in growth causing the death of the majority of trees during this period is consistent with bark identifying the death of one tree in the RY 197 and rings becoming too narrow to reliably measure in two other trees (one of which, bark suggests, probably died in 236 RY). All the trees probably died at this site by 245 RY. The one tree at the apparent centre of the site struggled on (with rings too narrow to be reliably measured) until death in about 286 RY. Together, the evidence indicates that the majority of trees germinated at this site between 5 and 85 RY and grew until radial growth became reduced to below 0.5 mm yr^{-1} between 197 and 245 RY. The cross-matched samples identify that pine occupied this site for a total of 280 years, but the oldest tree lived to an age of 196 and on average the trees lived for just 156 years.

Although not cross-matched in the site chronology, one 25 mm scar orientated to the north-east was identified early in the 32rd ring of sample BADA08.

3.2.3 Loch an Ruathair

Loch an Ruathair lies inland 25 km north north-west of the town of Helmsdale, which lies on the east coast of Scotland. The site itself extended along the south shore of the loch, just to the west of the A897 (Figure 54).

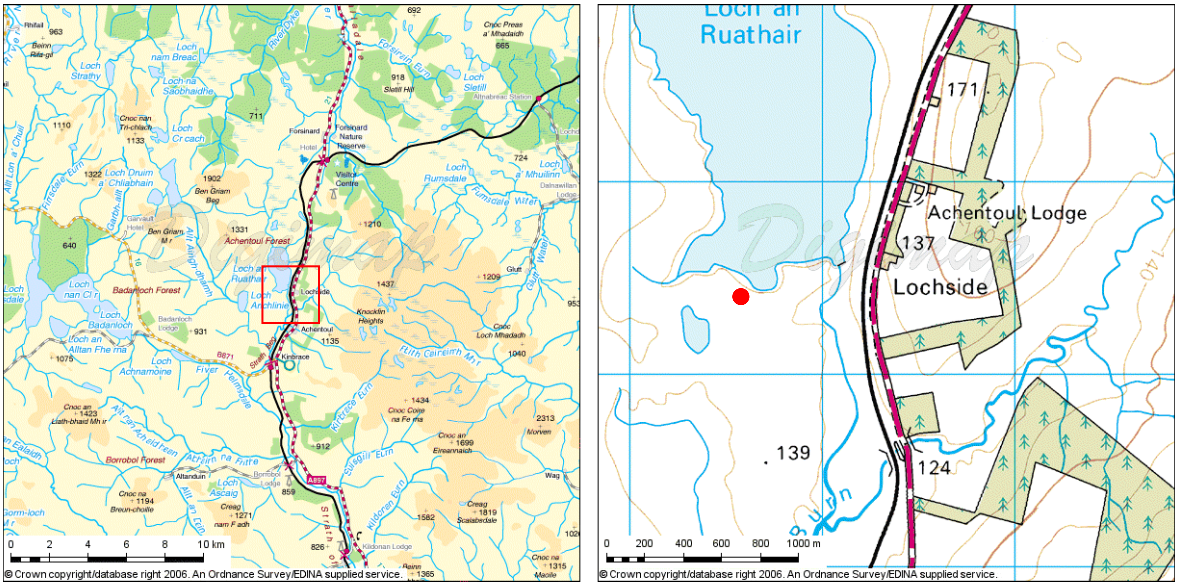

Figure 54: Loch an Ruathair area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

This valleyside mire site is exposed and treeless today (Figure 55). Pine-stumps had become exposed due to loch level fluctuations apparently enhanced more recently by the construction of a small dam for its use as a reservoir. Two distinct layers of pine stumps were observed and there was no evidence of peat cutting (Figure 56).

Figure 55 Loch an Ruathair site looking west, samples exposed through wave action and changing water levels. Photograph by: A. K. Moir, 2004.

Figure 56 Loch an Ruathair looking east, shows two horizons of pine and sample RATH14 (taken from the upper layer). Photograph by: A. K. Moir, 2004.

3.2.3.1 Cross-matching and stand dynamics

In June 2002, eighteen samples were collected and assigned the site code RATH. Twelve of the samples collected were of sufficient length to be measured. Eight sequences were cross-matched with a mean *t*-value of 3.62 and used to form a 232 year long chronology called RATH-8. This chronology was found to cross-match at a relative position of years 61 to 292 against other subfossil pine site chronologies and was included in the reference chronology named WRATH-9. Two remaining sequences (RATH09 and RATH16) cross-matched with a *t*-value of 8.15 and were combined to form a 102 year long chronology called RATH-B, however no further cross-matching using this chronology could be established.

The first tree at this site germinated in RY 55, followed by the germination of three trees at a mean rate of 1 every 7 years. Three trees are thought to have germinated in RY 102 or soon after (SD = 4.36, range 8 years). Mean radial growth peaks just over 1.00 mm yr^{-1} between RY 160 and 180. A narrow ring in RY 180 marks the decadal radial growth rate dropping under 1.0 mm yr^{-1} and gradual declining to 0.51 mm yr^{-1} starting in RY 250. Bark identifies that the first tree probably died in RY 234, followed by two in RY 296 and RY 298, and then two in RY 318 and RY 336. Together the evidence indicates that the majority of trees germinated at this site between RY 55 and RY 102. General growth rates declined under 1.00 mm yr^{-1} from RY 180. The first tree died probably in RY 234 and all but two of the trees sampled had died by RY 298 as one by one their growth was reduced to under 0.03 mm yr^{-1}. However, the site as a whole was occupied for at least 280 years as at least two trees struggled on until about RY 318 and RY 336.

3.2.4 Loch Ascaig

Loch Ascaig lies inland 20 km north-west of the town of Helmsdale which lies on the east coast of Scotland. The site is accessed past Borrobal lodge and is located on the eastern end of the loch (Figure 57).

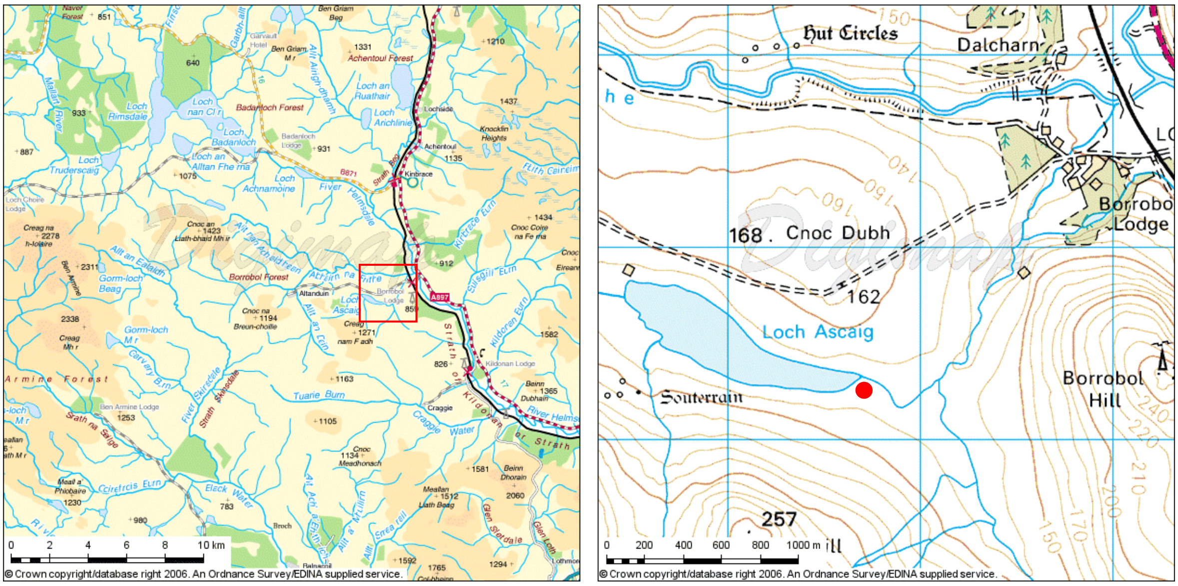

Figure 57: Loch Ascaig area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

This valleyside mire site is exposed and treeless today (Figure 58). Pine stumps appeared to have been exposed along the eastern edge of the loch through changes in water level. No peat cuttings were identified at this site and only one layer of pine stumps was observed (Figure 59).

Figure 58: Loch Ascaig site looking north-east. Photograph by: A. K. Moir, 2001.

Figure 59: Loch Ascaig showing poor sample preservation. Photograph by: A. K. Moir, 2001.

3.2.4.1 Cross-matching and stand dynamics

In September 2001, eight samples were collected and assigned the site code ASCA. The precise location of these samples was not recorded and therefore there is no diagram of the location of individual samples in Appendix II. All eight of the samples collected were of sufficient length to be measured. Three sequences were cross-matched and used to form a 184 year long chronology called ASCA-3. This chronology was found to cross-match at a relative position of years 63 to 246 against other subfossil pine site chronologies and was included in the reference chronology named WRATH-9. Three remaining sequences cross-matched to form a 190 year long chronology called ASCA-B, however no further cross-matching using this chronology could be established. The three trees cross-matched into the WRATH-9 chronology germinated in RY 47, 53 and 62. The mean radial growth for the site is 0.86 mm yr^{-1}. Decadal growth peaks at 1.50 and 1.42 mm yr^{-1}, between RY 160 and 180. No bark was identified from this site, but the final tree-ring measured ends in RY 246, suggesting that the site was occupied by Scots pine for about 200 years.

3.2.5 Loch Assynt

Loch Assynt lies inland 12 km east of the town of Lochinver which is located on the west coast of Scotland. The site lies near the centre of the 10 km long loch on the north bank (Figure 60). The loch is orientated north-west to south-east and is bounded by mountains over 500 m on either side.

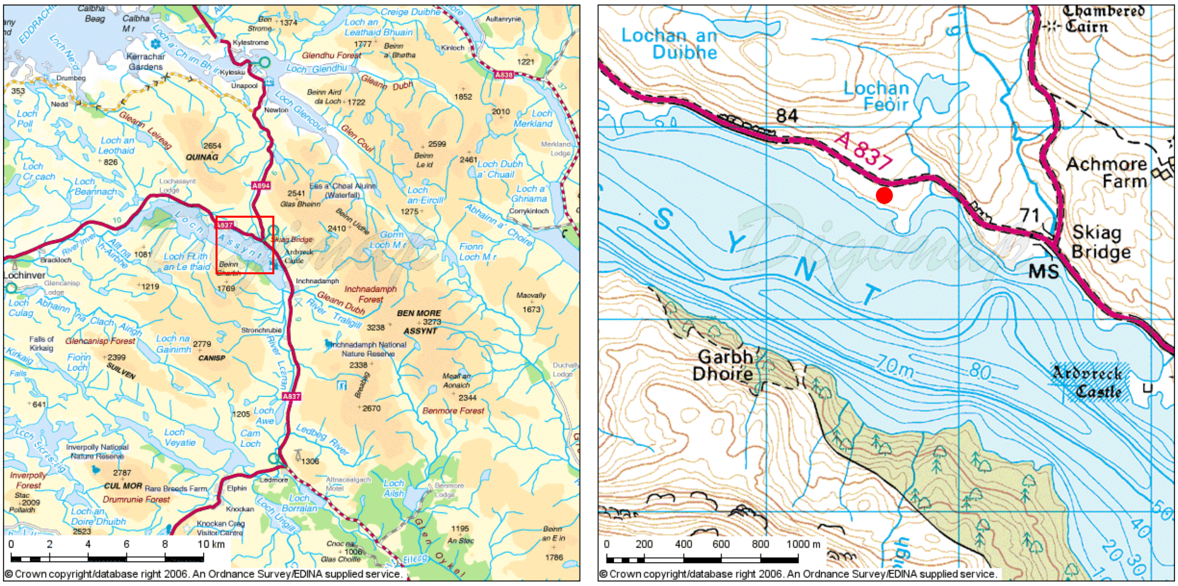

Figure 60: Loch Assynt area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

This valleyside mire site is exposed and treeless today (Figure 61). The pine stumps were mainly exposed in the drainage ditches of the A873 that bounds the north of the site. No peat cuttings were identified and only one layer of pine stumps was observed (Figure 62).

Figure 61: Loch Assynt looking south-east, the site bounded between the road and loch edge. Photograph by: A. K. Moir, 2001.

Figure 62: An eroded *in situ* pine stump at Assynt showing poorly preserved outer edge. Photograph by: B. A. Moir, 2001.

3.2.5.1 Cross-matching and stand dynamics

In June 2002, ten samples were collected and assigned the site code ASSA. Eight of the samples collected were of sufficient length to be measured. Four sequences were cross-matched with a mean *t*-value of 3.26 and used to form a 257 year long chronology called ASSA-4. This chronology was found to cross-match at a relative position of years 44 to 300 against other subfossil pine site chronologies and was included in the reference chronology named WRATH-9.

The first tree at this site germinated in RY 1, followed by the probable germination of two trees in RY 21 or soon after. The final tree dated at this site germinated 120 years later, in RY 142. Mean radial growth of the site mean peaks at just under 1.00 mm yr^{-1}. Decadal radial growth rate drops to its lowest (0.63) between RY 190 and 200, and rises to levels above 1.00 mm yr^{-1} for a 40 year period between RY 230 and 260, peaking at 1.51 mm yr^{-1} between RY 240 and 250. Both samples located near the centre of the sample area became too narrow for the rings to be reliably measured, indicating a deterioration in growth conditions from RY 188 and 236. Bark identifies that three of the trees dated all suddenly died in RY 296, 297 and 300, identifying that the site was occupied by pine for 300 years.

In the cross-matched samples, three scars were recorded in sample ASSA03. A 3mm scar orientated to the north-west occurred early in the 12th ring, one 3mm scar orientated to the west occurred early in the 15th ring and one 22mm scar orientated to the south-west occurred early in the 53rd ring. These scars occur respectively in RY92, 95 and 133 in the WRATH-9 chronology.

3.2.6 Loch Crocach

Loch Crocach lies 5 km east of Tongue, 5 km south of the northern coast of Scotland (Figure 63).

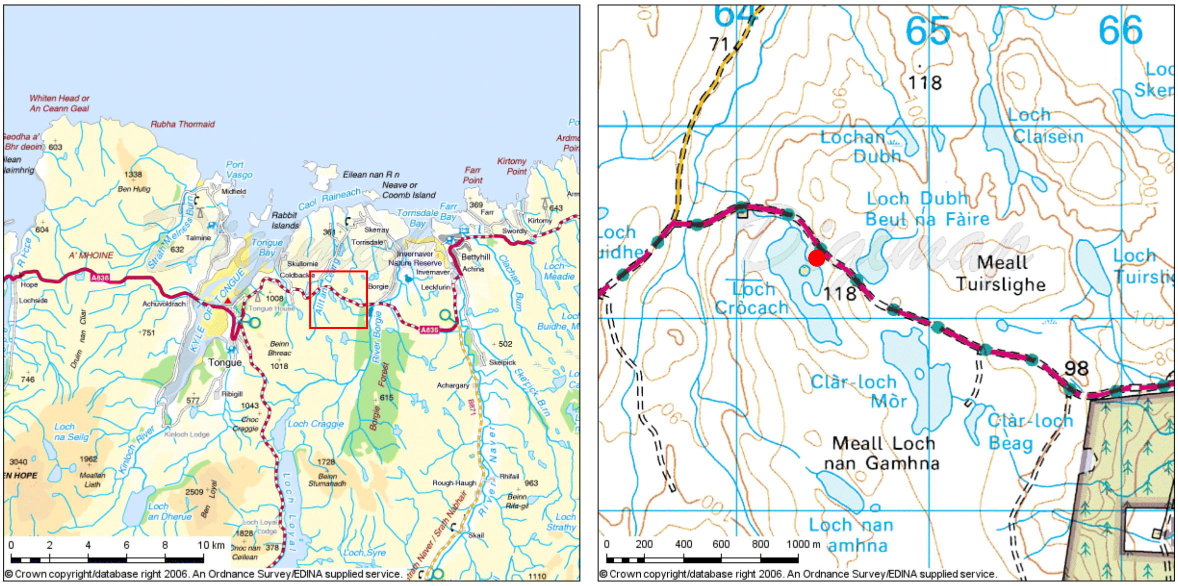

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Figure 63: Loch Crocach area and site location maps
Red square = area enlarged in map on the right, Red dot = location of site.

During site reconnaissance in September 2001, a cutting was located through a valleyside mire at this site. A dense layer of pine stumps had been apparently excavated and subsequently used to form a sculpture (Figure 64). A number of pine stump sections had been discarded during the operation and four suitable samples were collected and the site assigned the code CROC. The site is well exposed and treeless today (Figure 65).

Figure 64: Loch Crocach and Holocene pine recovered which has been arranged into a sculpture. Photograph by: A. K. Moir, 2001.

Figure 65: Loch Crocach cutting showing the extensive horizon of Holocene pine from this narrow cutting. Photograph by: A. K. Moir, 2001.

3.2.6.1 *Cross-matching and stand dynamics*

All four of the samples collected were of sufficient length to be measured. The samples were assigned the site code CROC. None of the sequences could be cross-matched together or with the other reference chronologies.

3.2.7 Loch na Thull

Loch na Thull lies 25 km south-west of Durness, 5 km inland from the west coast of Scotland (Figure 66).

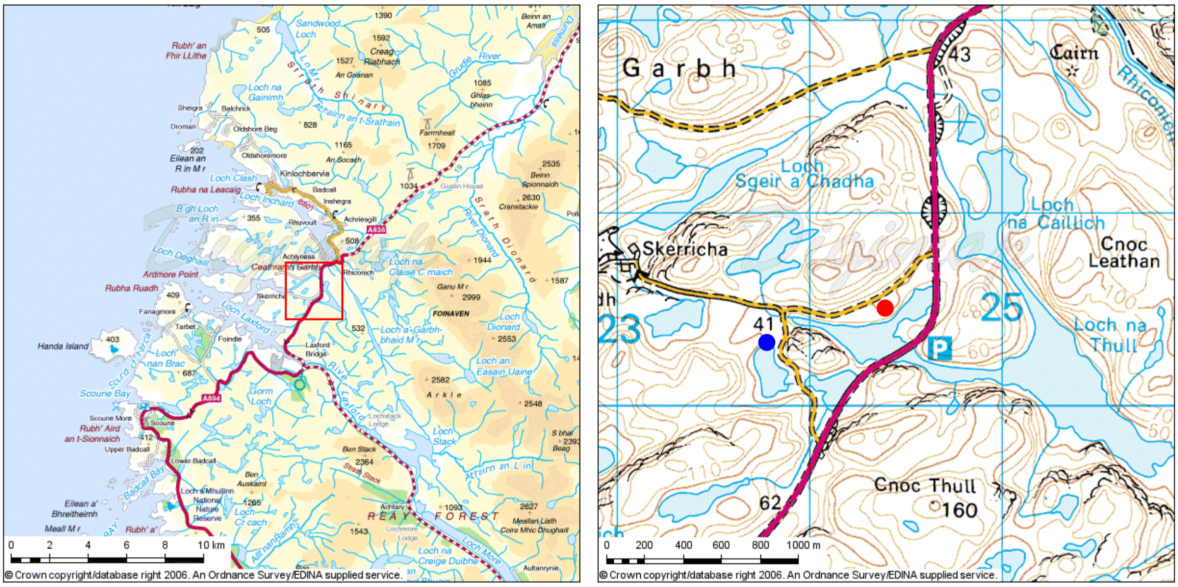

Figure 66: Loch na Thull and Skerricha area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of Loch na Thull, Blue dot = location of Skerricha.

This treeless valleyside mire site is located between the road to Skerricha and Loch na Thull end. A scattered single layer of pine-stumps appear to have become exposed through peat cutting (Figure 67).

Figure 67: Loch na Thull looking south. Photograph by: A. K. Moir, 2004.

3.2.7.1 *Cross-matching and stand dynamics*

In June 2002, four samples were collected and assigned the site code THUL. Three of the samples collected were of sufficient length to be measured. None of the sequences could be cross-matched, either together or with the other reference chronologies.

3.2.8 Polla on Loch Eriboll

This sample site lies 12 km south of the town on Durness which lies on the north coast of Scotland (Figure 68).

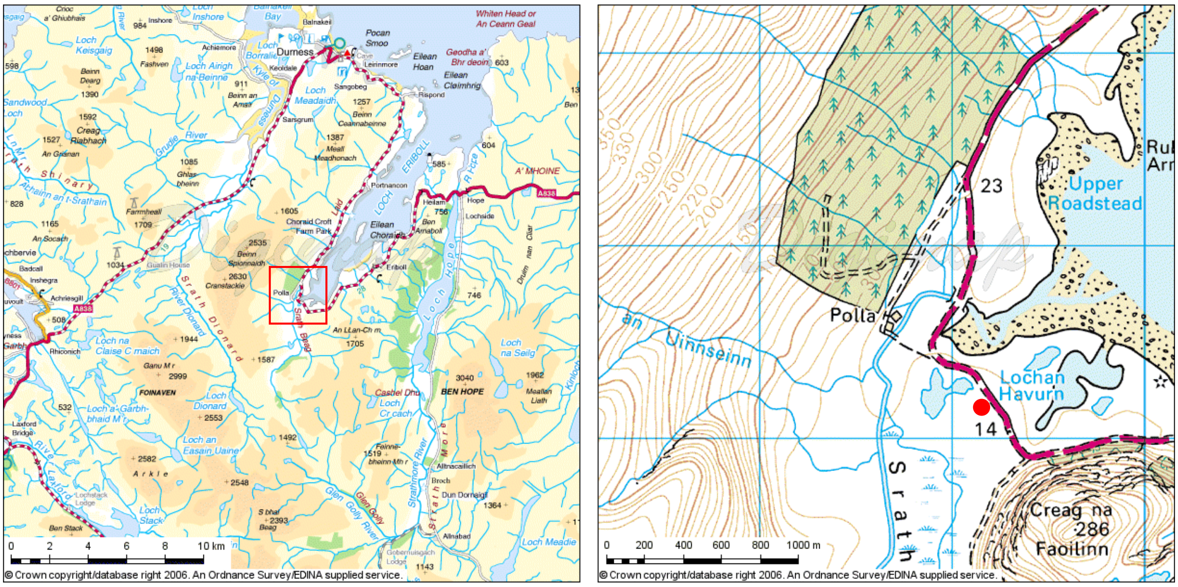

Figure 68: Polla area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

This treeless vallyside mire spreads just south-west of the A838, at the southern end of Loch Eribol (Figure 69). Two levels of pine stumps were observed. Peat cutting was clearly evident in the area (Figure 70).

Figure 69: Polla site looking north-east, area of samples POLL04 to POLL10, cotton grass indicative of the disturbance caused by peat cutting. Photograph by: A. K. Moir, 2004.

Figure 70: Polla site looking south-east, area of samples POLL01 to POLL03 in the foreground, the face of the peat cutting in the background demarcates the rear extent of the site. Photograph by: A. K. Moir, 2004.

3.2.8.1 Cross-matching and stand dynamics

In June 2002, eleven samples were collected and assigned the site code POLL. Ten of the samples collected were of sufficient length to be measured. Six sequences were cross-matched and used to form a 344 year long chronology called POLL-6. This chronology was found to cross-match at a RY 25 to 368 against other subfossil pine site chronologies and was included in the reference chronology named WRATH-9.

The first tree at this site germinated in RY 1, followed by the probable germination of the other five trees dated on an average of one every 10 years. The last tree dated at this site probably germinated by RY 52. The site mean has a mean radial growth rate of 0.71 mm yr^{-1}, this markedly drops to around 0.50 mm yr^{-1} in three decades starting RY 120, 210 and 300. Bark identifies that two trees dated died in RY 313 and 379, indicating that this site was occupied by Scots pine for 379 years.

In the cross-matched samples, two scars were recorded in sample POLL05. An 8 mm scar orientated to the west occurred early in the 25th ring, one 18 mm scar orientated to the north-west occurred early in the 66th ring. These scars occur respectively in RY83 and 100 in the WRATH-9 chronology.

3.2.9 Skerricha

Skerricha lies 25 km south-west of Durness, 5 km inland from the west coast of Scotland (Figure 66). This valleyside mire site is located at the north end of the loch (Figure 71). The site is treeless. A single layer of pine-stumps exposed through peat cutting was identified at this site (Figure 72).

Figure 71: Skerricha site looking north-west, pine stumps exposed at ground level in front of the peat cutting face. Photograph by: A. K. Moir, 2004.

Figure 72: Face of peat cutting spread of cotton grass attributable to disturbance by peat cutting. Photograph by: A. K. Moir, 2004.

3.2.9.1 *Cross-matching and stand dynamics*

In June 2002, fourteen samples were collected and assigned the site code SKER. Eleven of the samples collected were of sufficient length to be measured. Seven sequences were cross-matched and used to form a 161 year long chronology called SKER-7, which had a mean radial growth rate of 0.84 mm yr^{-1}. No further cross-matching of this chronology could be established.

3.2.10 Strath Canaird

Strath Kanaird lies 10 km north north-east of the town of Ullapool which lies on the west coast of Scotland (Figure 73).

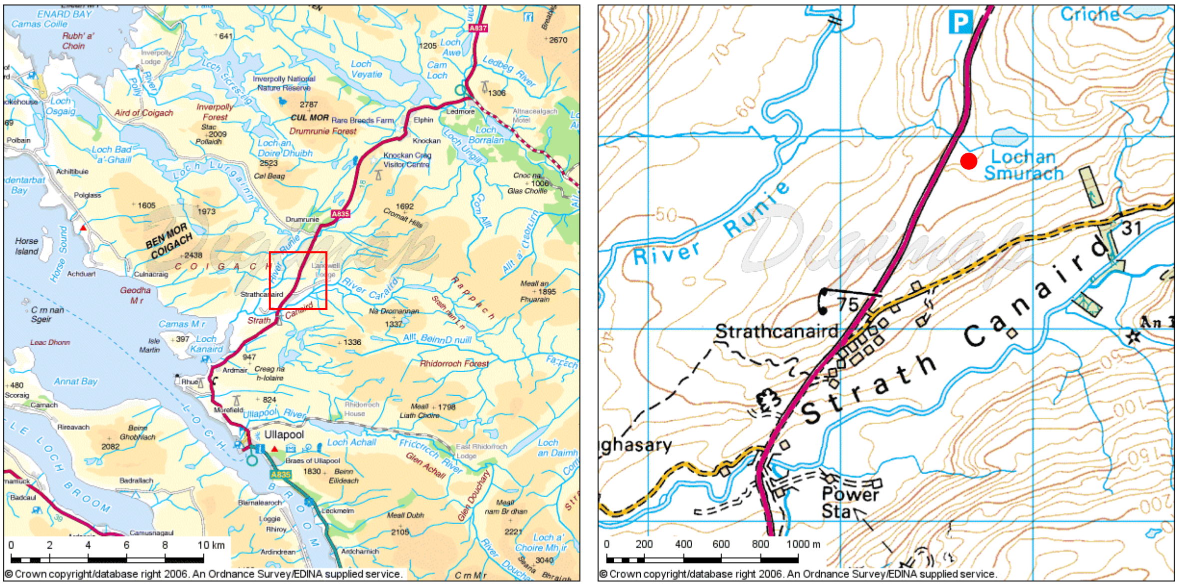

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Figure 73: Strath Canaird area and site location maps.
Red square = area enlarged in map on the right, Red dot = location of site.

This treeless spur mire site lies just to the east of the A835, on an exposed south-west spur of the Cromalt Hills (Figure 74). No evidence of peat cuttings were observed at this site, the pine stumps appeared to have become exposed through gully erosion (Figure 75).

Figure 74: Strath Kanaird site looking north-east. The extent of the exposure of Holocene pine corresponds approximately with the three telephone polls visible. Photograph by: A. K. Moir, 2004.

Figure 75: Strath Kanaird, showing Holocene pine exposed apparently by gully erosion. Photograph by: A. K. Moir, 2004.

3.2.10.1 Cross-matching and stand dynamics

In June 2002, thirty two samples were collected and assigned the site code SMUR. Twenty three samples collected were of sufficient length to be measured. Thirteen sequences were cross-matched with a mean *t*-value of 3.43 and used to form a 308 year long chronology called SMUR-13. This chronology was found to cross-match at a relative position of years 103 to 410 against other subfossil pine site chronologies and was included in the reference chronology named WRATH-9. Two remaining sequences (SMUR03 and SMUR07) cross-matched with a t-value of 5.88 and were used to form a 221 year long chronology called SMUR-B, however no further cross-matching using this chronology could be established.

The first two trees cross-matched at this site germinated in RY 85 and are located at the north-east of the sampling area. This is followed by the probable germination of eight trees in RY 97 (SD = 5.90, range 13 years). The final three cross-matched trees at this site germinate between at RY 119, 139 and 165 and are all located at the south-west end of the sampling area. Mean radial growth for the site mean is 0.91 mm yr^{-1}. Decadal radial growth briefly peaks over 1.00 mm yr^{-1}, at 1.37 mm yr^{-1} between RY 160 and 200.

Rings become too narrow to be reliably measured from RY 211 and 249, and together with the death of two trees in RY 244, 269, 318 and probably 259, all indicates that growth at the middle of the sampling area gradually became more restricted. The majority of trees had died by about RY 359, however 5 trees located on the north-east and south-west of the sample area survived until death in RY 394, 403, after 423, 430 and 443. While the majority of trees died between RY 244 and 359, a few survived until the last tree died in RY 443, indicating that this site was occupied for just less than 360 years.

3.2.11 Additional sites

Information was available from three additional Holocene pines sites at Badanloch, Loch Vatachan and Loch Shin (Daniell 1997). Both the Badanloch and Loch Vatachan chronologies are cross-matched in the WRATH-9 chronology (Table 7) and therefore their germination and decline are described in terms of years relative to this chronology (RY). The Badanloch chronology is made from 15 trees, 7 of which are identified to germinate within the first 25 years of the chronology. The two earliest samples in the chronology had missing or damaged centres, so germination is likely to be at 10 years earlier than the first trees identified to germinate at this site in RY 35. Pine is indicated to have grown at this site for about years 180 years, the first trees started dying after about 80 years of occupation. The Loch Vatachan mean chronology is made up of samples from 20 Scots pine trees, 9 of which are identified to germinate within the 1st 25 years of the chronology. The first Scots pine tree germinated in RY 41, the final tree died after RY 215. This indicates that pine grew at this site for 175 years, although all but three trees probably died between RY 120 and 160.

The Loch Shin mean chronology is made up of samples from 19 Scots pine trees, 16 of which are identified to germinate within the 1st 25 years of the chronology. The first Scots pine tree germinated in RY 6. Pine grew at this site for 220 years, although five tree ring sequences end in its ninth decade after germination and another seven in the sixteenth decade after germination.

3.3 Inter-site comparisons

In all cases, site chronologies are simply means of the individual component ring width sequences and the cross-matching reported between them expressed as t-values derived from the original CROSS73 algorithm {Baillie & Pilcher 1973 BAILLIE1973A /id}.

3.3.1 Modern Scots pine cross-matching and general statistics

The cross-matching of the Scots pine shows groups of higher *t*-values which are broadly consistent with different geographical and ecological areas along the north-west (NW) to south-east (SE) transect of northern Scotland (see Table 3 and Table 4). A prominent group grow on a mineral substrate under Hemioceanic conditions at the SE end of the transect. This group of eleven chronologies are distinguished by well replicated and consistently high cross-matching (mean t-value of 6.25). A second prominent group grows on a mineral substrate under Hyperoceanic and Euoceanic conditions at the NW end of the transect. This group of seven chronologies are distinguished by less well replicated and consistent cross-matching (mean *t*-value of 4.41). Glen Affric, a mineral substrate site which lies near the centre of the transect, shows good cross-matching with both the SE and NW groups.

The SE and NW groups of chronologies show broadly similar means in terms of the number of trees cross-matched, success rate of cross-matching and mean sensitivity, at 11:12, 91:94% and 0.14:0.15, respectively. Both mean ring width (1.17:1.48 mm yr^{-1}) and auto correlation (0.78:0.87) are respectively lower in the SE than the NW and this is unlikely to result entirely from the 39 year difference in the mean age between these groups. Mean *t*-values are highest (>5) at most sites above 380 m in the SE, but it is important to recognise that the NW group have only two sites above 130 m. The NW and SE mineral growing pine groups are also distinguished by their difference in cross-matching to adjacent pine chronologies that grow on peat. While the NW mineral group displays reasonable cross-matching with two local chronologies from pine growing on peat at Eilann Sùbhainn, the SW mineral group displays an almost complete absence of cross-matching to the three local chronologies from pine growing on peat at Abernethy.

The two peat substrate chronologies at Eilann Sùbhainn cross-match well together (*t*-value = 7.1) and the three Abernathy chronologies extremely well (*t*-values >11.5). In comparison to Scots pine growing on a mineral substrate, these chronologies have a much lower mean ring-width (growth rates are further compared in section 3.3.2), but otherwise have similar ranges of sensitivity and auto correlation (ranging from 0.16-0.22 and 0.77-0.92 respectively). The peat growing chronology from Pitmaduthy Moss has a mean radial growth of 0.83 mm yr^{-1}, compared to 2.36 mm yr^{-1} for its mineral counterpart. There is an absence of cross-matching between these two chronologies. Short length, peat and mineral substrate chronologies developed from Inshriach cross-match together with a *t*-value of 5.2. Both have high radial growth rates (>2.35 mm yr^{-1}) and low mean intra-site cross-matching (>4). Two peat substrate chronologies from Monadh Mor fail to cross-match together and both have low mean cross-matching (>3.70) and mean radial growth in comparison with most mineral substrate chronologies (>1.3 mm yr^{-1}).

Within restricted geographical units, trees of the same species growing at the same time usually show similar trends in annual increment growth. The results of cross-matching suggest that in northern Scotland, not only do differences in the annual increment of pine occur over relatively short distances (about 100 km) between trees growing on mineral substrate, but also between adjacent pine growing on a mineral and peat substrate.

3.3.2 Radial growth rates comparing both mineral and peat substrate sites

Plots of the cumulative ring-width of growth trend sequences highlight most Scots pine growing on a mineral substrate (Figure 76) have higher radial growth rates than pine growing on peat substrate (Figure 77).

Rates of radial growth for Scots pine growing on mineral substrate display the normal gradual reduction in growth associated with age, their formative radial growth is typically about 2 mm yr^{-1}, mature radial growth about 1.5 mm yr^{-1}, the change between these stages typically occurring after 55 to 85 years. In comparison, Scots pine growing on peat show little or no age trend, the radial growth rates are mostly between 1.0 and 0.5 mm yr^{-1} and remain fairly constant throughout the age of the tree. A formative radial growth rate growth is generally quoted to allow comparisons to be made between sites with the minimum influences of age differences or crown competition this is taken as the mean radial growth rate at an age of 55 years.

Scots pines growing on mineral substrate have formative radial growth rates between 1.03-3.83 mm yr^{-1}. Scots pine from the sites at or under 100 m on the NW coast (Mallaig, Plockton, Shieldaig and Loch Maree) show the highest formative radial growth rates ranging from 2.17-3.83 mm yr^{-1}; pine from sites over 100 m altitude in the SE (Ballochbuie, Inverey, Dimmie, Glen Derry, Abernethy) the middle range of 1.75-2.22 mm yr^{-1}; pine at over 120m sites in the NW (Coulin, Achanalt, Beinn Eighe and Glen Affric) the lowest range of 1.03-1.68. The only exception to this general pattern is the 50m altitude site in the NW at Eilann Sùbhainn which has a lower than expected formative growth rate of 1.77 mm yr^{-1}. However this site appears unusual in another respect as the rate of growth reduces to less than 1.00 mm yr^{-1} after 55 years. The extreme northern sites at Strathnaver and Borgie show similar formative radial rates of growth at 1.79 and 1.86 mm yr^{-1} respectively for interior forest Scots pine. Interestingly pines sampled from the windblown site at Strathnaver show a much lower rate of 1.17 mm yr^{-1}.

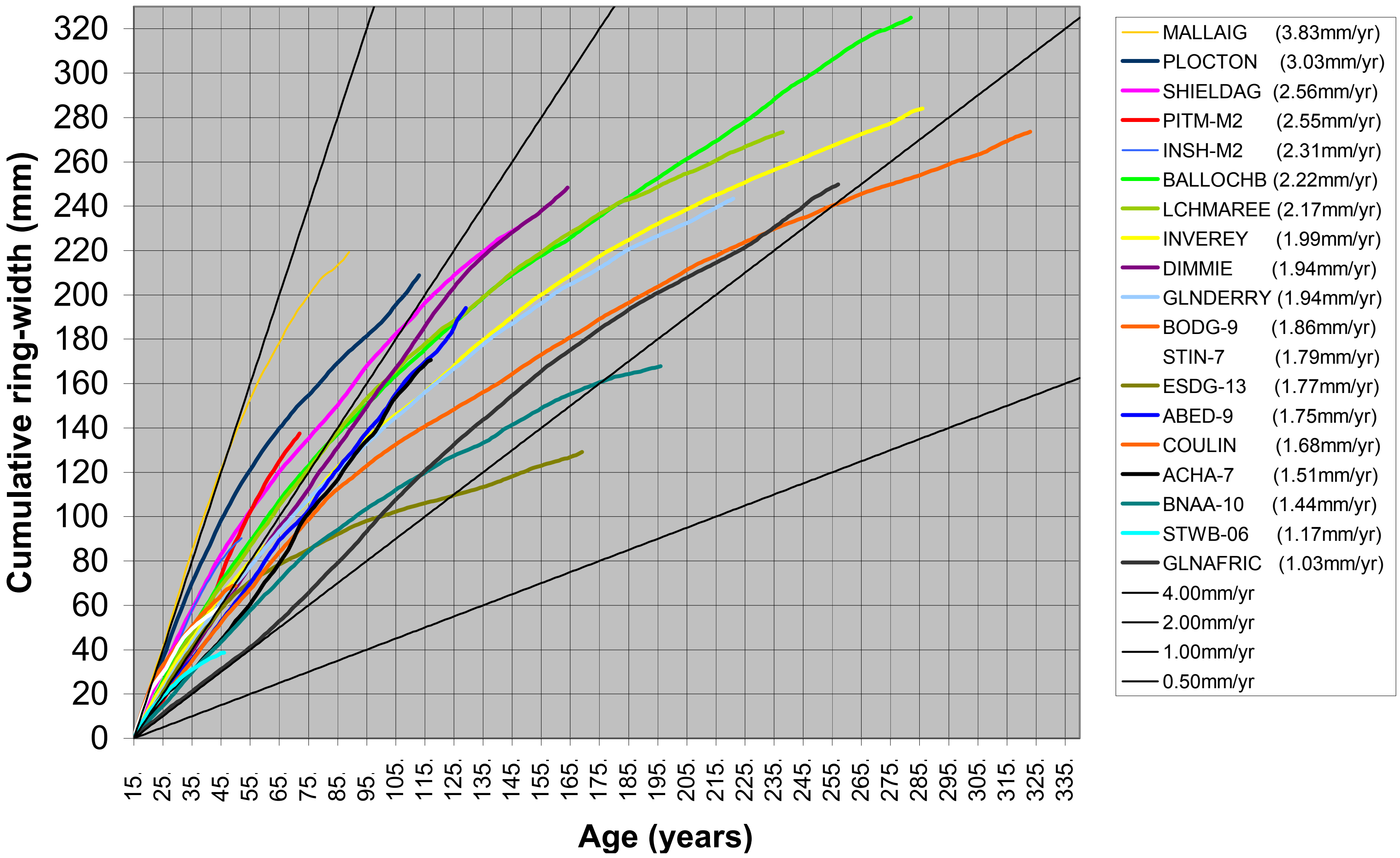


Figure 76: Plots of the cumulative ring-width of Modern pine growing on a mineral substrate, formative growth rates also shown.

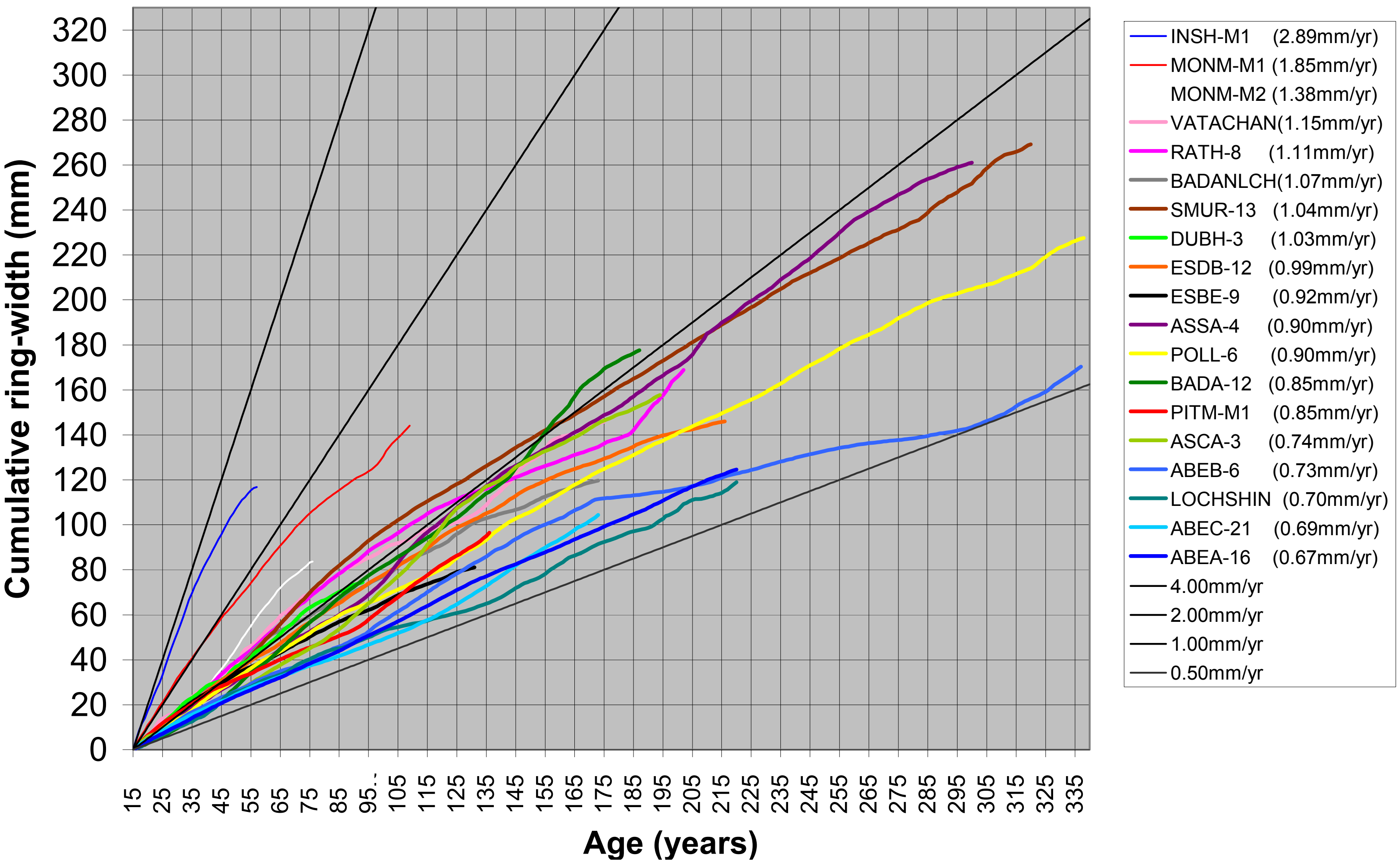


Figure 77: Plots of the cumulative ring-width of Modern and Holocene pine growing on a peat substrate, formative growth rates also shown.
The component sequences of BADANLOCH, LOCHSHIN and VATACHAN were not available and therefore the site means and not age trend means are plotted.

The most direct comparisons of the growth rates of Scots pine on mineral and peat substrates are at sites where chronologies were developed for both substrates. At Abernethy the Scots pine on a mineral substrate has a formative radial growth rate of 1.75 mm yr^{-1}. In comparison, the three pine sites on bog fail to achieve growth over 0.75 mm yr^{-1}. At Eilean Sùbhainn the Scots pine has formative radial growth rate of 1.77 mm yr^{-1}, while pine growth on the two bog sites have growth rates under of 1.00 mm yr^{-1}. Similar to the pattern in the mineral sites, the 50m altitude NW site at Eilean Sùbhainn has a higher radial growth rate than the 220m altitude Abernethy site in the SE. Scots pine growing on a mineral substrate at Pitmaduthy Moss has a formative radial growth of 2.55 mm yr^{-1}, those on a bog 0.85 mm yr^{-1}.

The evidence from three locations (Abernethy, Eilean Sùbhainn and Pitmaduthy Moss) suggest that Scots pine growing on mineral substrate has formative radial growth rates over 1.50 mm yr^{-1}, while that on adjacent bogs has rates under 1 mm yr^{-1}. However, there are three exceptions. Pine trees growing on a peat substrate at Inshriach have higher growth rates than those growing on a mineral substrate: formative radial growth rates of 2.89 mm yr^{-1} and 2.31 mm yr^{-1}, respectively. Only two trees were cross-matched from peat at Inshriach and these are likely to have been from shallow cut-over peat rather than active bog. This site also had an extremely low success in cross-matching, which suggest that the site has been disturbed and it is considered unlikely that the site is characteristic of pine growth on peat. Two chronologies were developed from pine growing on bog at Monadh Mor, but these chronologies failed to cross-match with each other. As both were developed from pine growing on bog, there is no comparison for pine on a mineral substrate.

3.3.3 Holocene Scots pine cross-matching and general statistics

Insufficient Holocene chronologies are cross-matched to identify clear geographical groupings (see Table 5 and Table 7). Nevertheless, expectedly the two closest sites produce the highest cross-matches:

- Druim Bad a' Ghaill and Loch Vatachan, 6 km apart, produce a *t*-value of 7.24
- Loch an Ruathair and Badanloch, 9 km apart, produce a *t*-value of 6.62

Good cross-matches (*t*-value >5) are also evident over greater distances between sites:

- Strath Kanaird and Loch an Ruathair, 80 km apart produce a *t*-value of 6.23
- Druim Bad a' Ghaill and Badanloch, 74 km apart produce a *t*-value of 5.58

The seven chronologies cross-matched in WRATH-7 have a mean 69% success rate of cross-matching between samples, compared to an overall 86% rate for the modern samples. However, more samples were taken from the subfossil pine sites and so the site chronologies contain a similar mean number of trees as the modern chronologies (about 10). The component site mean chronologies of the WRATH-7 chronology cross-match with a mean *t*-value of 3.87. The WRATH-7 chronology contains trees with an overall mean age of 158 years, mean ring width of 0.85 mm yr^{-1}, mean sensitivity of 0.20 and auto correlation of 0.77. Strath Kanaird is located at an altitude of 360 m, but the other subfossil pine sites are located below 150m. Problems in cross-matching were normally caused by missing rings in the first and last 50 years of growth, particularly in consecutive rings under 0.20 mm. Where these problems could not be resolved, the beginning and/or end sections were ring counted.

3.3.4 Tentative dating of the WRATH-9 chronology to span *c.* 3200-2790 BC

Two site mean chronologies developed from Badanloch and Loch Vatachan by Daniell {Daniell 1997 DANIELL1997 /id /d} cross-matched with the WRATH-7 chronology (Table 7). These two chronologies were incorporated to establish a WRATH-9 chronology which failed to date (section 3.2). Difficulties identified during the cross-matching of the component site chronologies suggested that periods of extremely narrow ring growth (under 0.20 mm), particularly near the beginning and ends of tree-ring sequences, commonly resulted in missing rings. To further attempt to date the WRATH-9 chronology, it was edited to a length that was replicated by at least three component chronologies. This established a 230 year long sequence which was called WRATH-9ED. Relative to the WRATH-9 chronology, this chronology spans RY61-290. The WRATH-9ED chronology was found to produce a good 5.70 *t*-value with the first ring of the sequence at 3139 BC and the final ring of the sequence at 2910 BC. Significant cross-matching at this position can be replicated against a number of other chronologies (Table 8).

Table 8: Tentative dating for the WRATH-9ED chronology at 3139-2910 BC against established reference chronologies from N. Ireland

Filenames	**Start dates**	**End dates**	***t*-value**	**Location & Short reference**
PINE3000	3177BC	2642BC	5.70	Mean Irish pine chronology (Pers. comm. D. Brown 2007)
SHARVOG1	3177BC	2642BC	4.56	Shavogues (Pilcher *et al.* 1995)
BALLYMC5	3138BC	2766BC	3.88	Ballymacombs More (McNally and Doyle 1984)
GARRYBOG	3418BC	2952BC	3.85	Garry Bog (Brown 1991)
BALLYMC3	3147BC	2630BC	3.81	Ballymacombs More (McNally and Doyle 1984)

Note: The PINE3000 chronology contains 1 tree from Sluggan Moss, 8 trees from Ballymacombs More and 9 trees from Sharvogues.

The dating of the WRATH-9ED is supported by the earlier crossdating of one of its component chronologies. A filtered version of the BADANLCH chronology is dated to span 3155-2983 BC against the Sharvogues chronology from N. Ireland, with a *t*-value of 4.02 (Daniell 1997).

Additional supportive evidence for the correct dating of the WRATH-9ED chronology is provided by ^{14}C dates. One sample from the Strath Kanaid and one from Loch an Ruathair site chronologies were sent for radiocarbon dating at the ^{14}CHRONO Centre (Queen's University of Belfast). A ^{14}C sample (UBA-8469), taken from rings 30-50 of SMUR20, produces a date of 4335 ±31 uncalibrated ^{14}C yr BP, which on calibration gives an estimated age range of 3050–2850 ^{14}C cal. yr BC. A ^{14}C sample (UBA-8470), taken from rings 40-60 of RATH12, produces a date of 4409 ±32 uncalibrated ^{14}C yr BP, which on calibration give an estimated age range of 3350–2900 ^{14}C cal. yr BC. These two ^{14}C dates are combined with three previous ^{14}C dates for samples cross-matched within the WRATH-9 chronology. As the relative positions of all five ^{14}C dates from the chronology are known (Table 9), wiggle matching of the ^{14}C dates was conducted using OXCAL 4.0 (Reimer *et al.* 2004) to calculate the sequence to span 3029-2936 ^{14}C cal. yr BC within 95.4% limits.

Table 9: ^{14}C dates and relative positions in the WRATH-9 chronology

Location	14C code	C14 date	S.D.	cal. BC 2σ range start	cal. BC 2σ range end	Dendro sample	Span of rings start	Span of rings end	Mid point	Gap
Loch Vatachan	SRR-5814	4570	45	3500	3100	VAT014	78	114	96	34
Loch Raithair	UBA-8470	4409	32	3350	2900	RATH12	120	140	130	36
Badanloch	SRR-3566	4405	50	3350	2900	BAD011	141	191	166	19
Badanloch	SRR-3567	4370	50	3350	2850	BAD012	170	200	185	7
Strath Kanaird	UBA-8469	4335	31	3050	2850	SMUR20	182	202	192	10

A wiggle match date of 3029-2936 ^{14}C cal. yr BC is produced for the ring sequence between RY 96-192, whereas the dendrochronological dates identified for this same sequence are 3104-3008 BC (a difference of just 75 years). The wiggle matched ^{14}C dates are considered sufficiently close to reinforce the date found from dendrochronological dating. While the WRATH-9ED sequence is tentatively dendrochronologically dated, the failure of the WRATH-9 chronology to match at the same relative position suggests there may be missing rings at the beginning and/or end of this longer chronology. Due to this problem, in most cases the WRATH-9 is discussed in terms of relative years (RY). Nevertheless, assuming the chronology is only a few years in error, this analysis indicates that RY0 of the WRATH-9 chronology equates to *c.* 3200 BC and the end of the chronology RY410 equates to *c.* 2790 BC. This dates the chronology in archaeological terms to the end of the Neolithic (a traditional archaeological subdivision of cultural periods spanning about 4000-2500 ^{14}C cal. yr BC).

3.3.5 Characteristics and timings of a Holocene Scots pine advance

Most subfossil samples were measured from pith and just under half measured to bark (or probable bark). The recovery of bark provides important information on the character, precise timing, and extent of this late Neolithic northward extension of pine to well beyond its present day limits (Figure 4).

The germination of pine is identified to have occurred at three sites (Druim Bad a' Ghaill, Loch Assynt and Polla on Loch Eriboll) almost simultaneously (within a range of 5 years). These sites are located over a distance of 60 km (between Ullapool and Durness) on the west coast of the north-west of the Highlands of Scotland and there their altitude decreases from 130 m in the south to 10 m in the north (Figure 78). From the initial phase of germination, year 1 in relative years (RY), many of the samples from these three sites could only be ring counted, due to the rings being too narrow to be reliably measured. Despite initial slow growth rates, a steady recruitment of pine seedlings at four other lowland sites during the first 55 years, show that pine extends over a total area of about 60 km^{2}. Pine germination extends eastwards and inland as identified at Badanloch, Loch Ascaig and Loch an Ruthair in RY 35, 47 and 55, respectively. This group of three sites lies within 10km of each other and the sites are at similar altitudes ranging between 120-140 m. Germination of pine occurs at Loch Vatachan (which has an altitude of 20 m) in RY 41. The final two sites where pine is identified to germinate are Strath Kanaird in RY85 and An Dubh-loch in RY95, these are respectively, the highest site sampled at an altitude of 360 m, and the most northerly sampled at latitude 58°30' north.

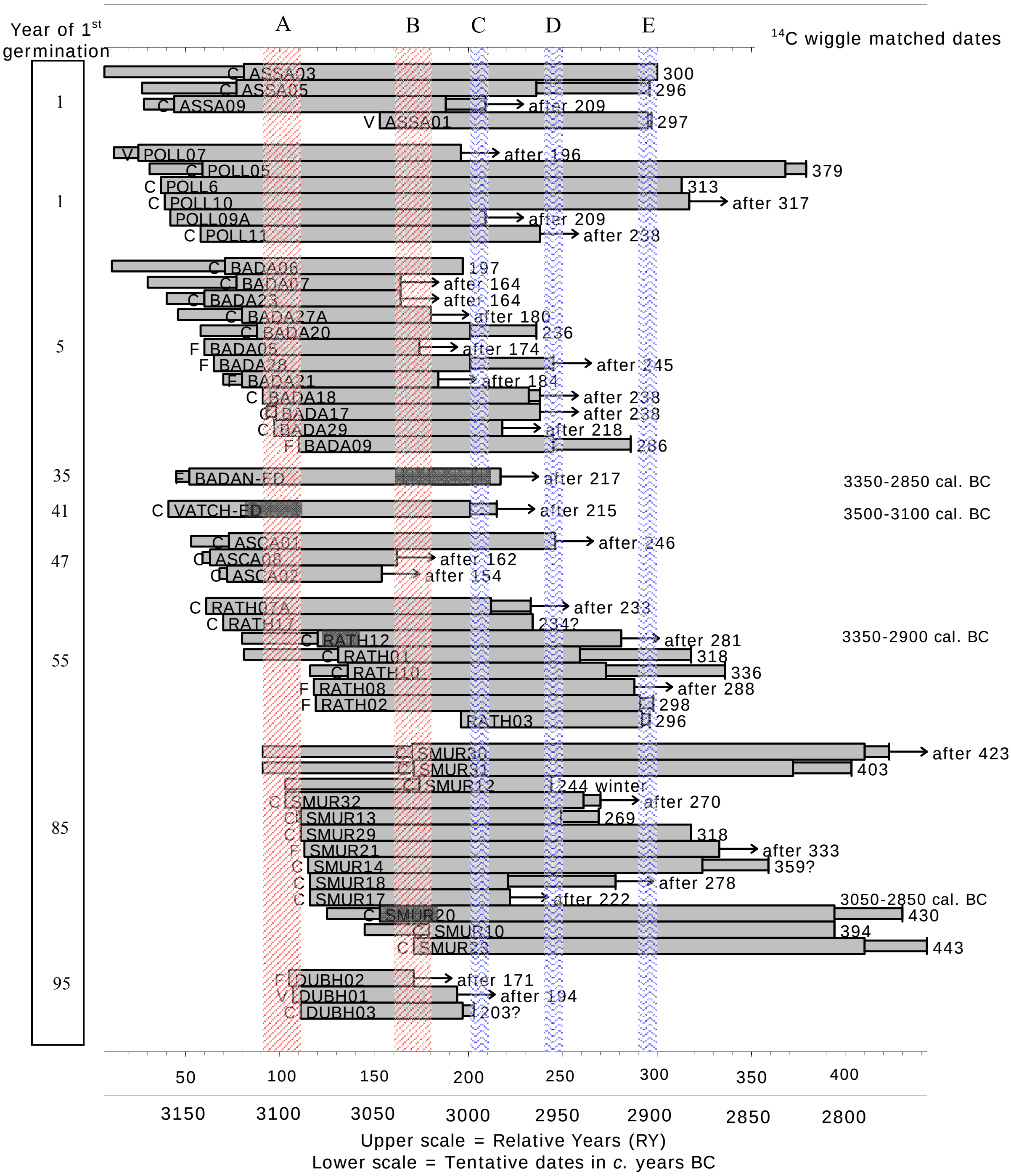


Figure 78: Bar diagram showing the span of tree-ring sequences cross-matched in the WRATH-9 chronology and highlighting periods of germination/mortality.
Diagonals highlight common periods of high germination & high radial growth rate (A), and high radial growth rate (B). Waves highlight common periods of low radial growth rate and increased mortality (C to E). Dark gray on bars indicate the position of 14C dated sections.

Five of the subfossil pine from Loch Assynt, Polla on Loch Eriboll, Druim Bad a'Ghaill and Loch Ascaig are consistent with the evidence from modern pine at six peat substrate sites, which indicates that the formative radial rate of growth does not exceed 1.00 mm yr^{-1}. However, the subfossil pine chronologies established from Loch Vatachan, Loch an Ruathair, Badanloch, Strath Kanaird and An Dubh-loch just exceed this rate, with a range between 1.03 to 1.15 mm yr^{-1}. Decadal radial growth rates identify only two periods common between the cross-matched chronologies when rates over 1.00 mm yr^{-1} occurred;

these periods occur between RY 90-110 and RY 160-180 (see A + B in Figure 78). The first of these periods of high radial growth (above 1.00 mm yr^{-1}) between RY 90 and 110 coincide with a second main period of germination at Strath Kanaird (the highest site at 360m) and An Dudh-loch (the most northern site, with a height of 140m). Radial growth rates peak again above 1.00 mm yr^{-1} during the second period at seven sites and an increase is also show at Badanloch. The germination of pine at Loch Assynt and Strath Kanaird suggest that conditions favourable for germination of Scots pine on bog continued until RY 165 when the final sampled pine germinated at Strath Kaniard.

The decline of pine across the region appears to occur in three main episodes starting from RY 197. All the cross-matched site chronologies show a sharp decrease in radial growth in the decade starting RY 197 (Figure 79). Bark also identifies the first mortality of trees occurring at Druim Bad a' Ghaill in RY 197 and An Dubh-loch in RY 203 (Figure 78). The sequences of five trees from Druim Bad a' Ghaill, two at Loch Ascaig and one from An Dubh-loch end before RY 197, but none of these sequences are recorded to bark edge. The mortality of all the trees sampled at An Dubh-loch occurs during this period. Sequences which end, or reduce in radial growth to a level where they could not be reliably measured, appear widespread at this time, e.g. at Loch Assynt in RY 188, Loch Shin in RY 189, Polla on Loch Eriboll in RY 196, Loch Vatachan in RY 210, Loch an Ruathair in RY 212 and Strath Kanaird in RY 221. Another period of high mortality and reduction in radial growth to a level that prevented reliable measurement occurs around the decade starting RY 240. This affects Loch Assynt in RY 236, Druim Bad a' Ghaill in RY 236, Loch an Ruathair in RY 234, and Strath Kanaird in RY 244. Between these two periods of lower radial growth and higher mortality, the samples indicate pine stopped growing at the Loch Ascaig, Loch Vatachan, Badanloch and Loch Shin sites. Additionally, all but one of the eleven trees that were growing at Druim Bad a' Ghaill died: just one tree survives from RY 245 at a radial growth rate too low to be reliably measured.

The final main episode of pine decline occurs in the decade starting RY 290. The last tree identified growing at Druim Bad a' Ghaill dies in RY 286. The death of two trees at Loch an Ruathair in RY 296 and 298 left only two of the sampled trees growing: both these trees continued at a rate that could not be reliably measured until their demise in RY 318 and 336. Three of the four trees sampled at Loch Assynt also died about this time in RY 296, 297 and 300. Only at Polla on Loch Eribol and Strath Kanaird are pine evident which survive more than three hundred and fifty years after germination. At Polla on Loch Eribol one pine sampled survives until RY 379. At Strath Kanaird trees grew until bark identifies the deaths of four trees in RY 394, 403, 430 and 443 and one after 423.

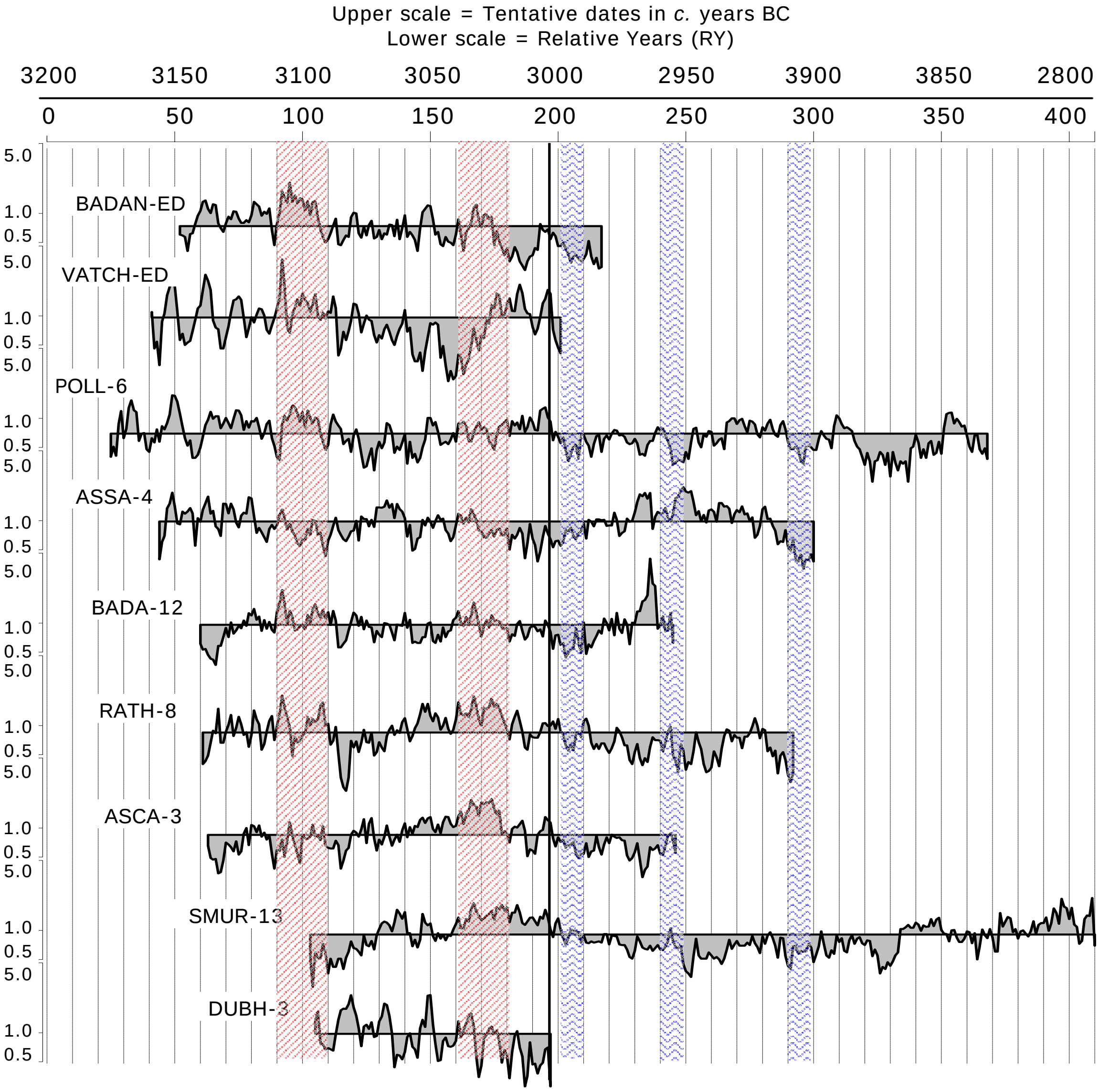


Figure 79: Ring-width plots of the cross-matched site masters of subfossil Scots pine, the solid vertical line marks the downturn or end of radial growth associated with RY 197 (*c.* 3003 BC). Diagonals highlight common periods of high radial growth rate. Waves highlight common periods of low radial growth rate. Ring width (mm) is plotted on a logarithmic scale on the y axis which starts at 0.5 mm and ends at 5.0 mm.

3.3.6 The preservation of Holocene Scots pine

The majority of subfossil pine sites sampled were on the west and northern coasts of the Highlands, under present day Hyperoceanic climate conditions. It has been assumed that the peat surface was at the level of the trunk/root collar interface at death and the height of the trunk preserved related to the speed it took for the peat to submerge the stump in its catotelm.

Due to limited data on the preservation of subfossil pine samples in peat (Table 10), only general observations are made. The 41 records of Holocene pine identify a mean stump height of 0.29 m. All the roots observed show morphological characteristics of growth in wet conditions, e.g. distinctive “I” girder roots, relatively shallow root growth and no tap root. Fifty two percent of the samples cross-matched were recovered with bark (which has not previously been recovered with subfossil pine sites in Scotland). The high bark recovery suggests quite rapid preservation conditions. The timing of periods of high or low preservation potential can be inferred from a number of sources. Bark was not recovered with any samples before RY 197. The eight samples ending before this date all have eroded outer rings. This suggests conditions of lower preservation potential existed before RY 197. Between RY 197 and RY 443 the preservation of bark suggests a period of relatively higher preservation potential. No samples that cross-matched were identified to have germinated after RY 165, which indicates that the peat surface was less suited for Scots pine germination after this time.

Table 10: Scots pine stumps preserved in the Highlands peat of Scotland

Site	Samples cross-matched	Mean stump height (m)	Mean root depth (m)	% samples with bark	Mean peat depth
An Dubh-loch	3	?	?	33%	?
Druim Bad a'Ghaill	12	0.12	0.43	25%	0.62
Loch an Ruathair	8	0.24	0.57	63%	1.11
Loch Ascaig	3	0.40	0.50	33%	?
Loch Assynt	4	0.33	0.46	75%	1.60
Polla on Loch Eriboll	6	0.44	?	63%	1.11
Strath Kanaird	13	0.32	0.50	69%	2.10

Note: Some samples recorded with bark at recovery could not be later measured to bark during analysis.

Where pine stumps are preserved it is reasonable to expect that continuous peat accumulation has occurred. The height of a stump preserved is expected to give an indication of the speed of mire growth after the death of the tree. Stump height and root depth were plotted over time (Figure 80) to attempt to identify periods of increased peat accumulation and periods of decreased water table respectively. The maximum stump height and root depth was 0.72 and 0.80 m respectively. All but seven of the samples preserved and cross-matched died between RY 160 and 340. Three sites (Loch Assynt, Druim Bad a' Ghaill and Loch an Ruathair) have a mean range from the first preserved to last preserved samples of *c.* 100 years. Two sites (site codes POLL and SMUR) have longer 183 and 221 year ranges respectively. The periods of higher mortality (earlier identified in section 3.3.5) are evident again between RY 240 and 290. Probably too few samples are recorded to identify either overall or site specific relationships.

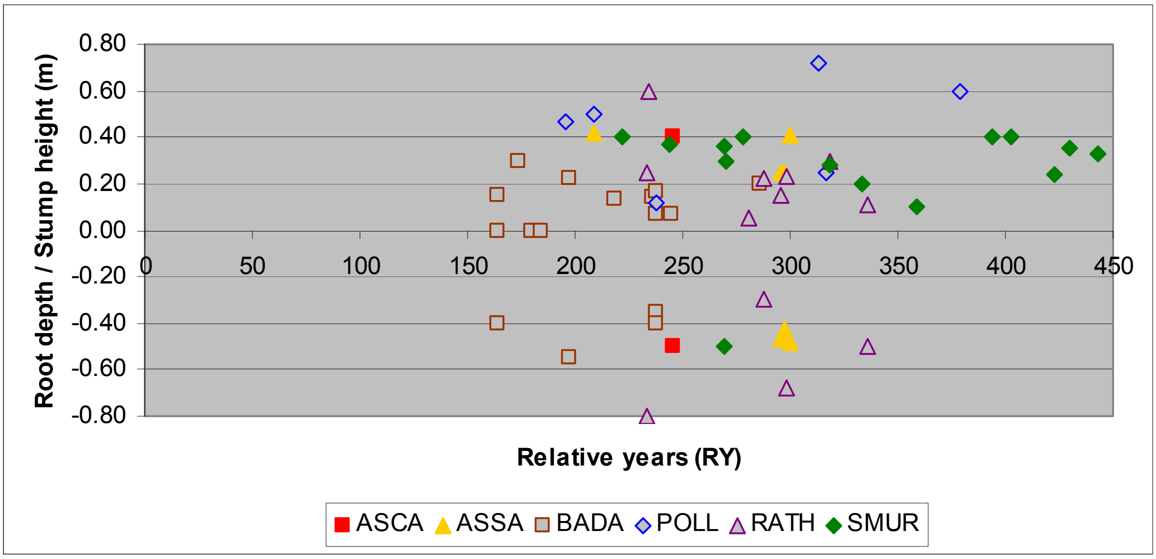


Figure 80: Stump height and root depth of Holocene subfossil Scots pine.

3.3.7 Scars in modern and subfossil bog pine

Few scars were identified in either modern cores or full sections of subfossil pine (Table 11). Of the 174 cores from modern sites, only 2% produced scar information. However this is an overestimate, because two scars were visually observed in the field and so deliberately targeted for coring. Of the 106 sections of subfossil pine measured, 3% produced scar information. Due to narrow rings it was not always possible to identify whether scars occurred early or late in a season.

The fire scar identified in sample ABEA05 occurred when ring width measurements indicate the tree had a diameter of 3.8 cm. In studying modern trees, Kolström and Kellomaki (1993) identify 5 cm as a minimum diameter of trees able to survival from fire, but it is assumed that this minimum included bark. For comparison to this study (which does not include bark) a minimum diameter of 4cm for tree survival from fire is thought appropriate. To tentatively differentiate between fire scars and mammal scars in this analysis, a 3.8 cm critical diameter value was used. This being the minimum diameter of a pine tree positively identified to have survived with a fire scar in this analysis (Table 11)

Seven scars occur in trees that were over 3.8 cm diameter. Fire scars occur in *c.* 1887 and 1920 in two modern bog pine samples from Abernethy. Following the *c.* 1887 firescar, the tree shows reductions in ring width of 15 and 47 percent in the subsequent 2 and 20 year periods. A lack of change in the ring widths of the site and surrounding two site chronologies suggest this fire was localised. Whereas, the tree firescared in 1920 shows a 31% reduction in ring width in the subsequent 2 years and an 8% increase in the subsequent 20 year period. Significant reductions in ring width over 2 and 20 year periods following the fire in both the site and surrounding chronologies indicate that this fire was widespread. Fire scars occur in 1923 and 1961 in two modern bog pine samples from Eilean Subhainn. Following the 1923 firescar, the ring width shows reductions of 80 and 38 percent in the subsequent 2 and 20 year periods. The 1961 firescared tree shows a 47% increase in ring width in the subsequent 2 years and a 21% decrease in the subsequent 20 year period. Significant reductions in ring width over 2 and 20 year periods following both the 1923 and 1961 fires in the two mean site chronologies developed at Eilean Subhainn suggest that these fires were widespread.

Table 11: Long and short terms differences in ring width following scars and interpretation of cause

Site	Sample type	Sample Code	Diameter at scar (cm)	Scar length (cm)	Scar height (m)	Scar Orient-ation	Mean ring width (mm)	Sum of prior 2 rings (100=1 mm)	Sum of latter 2 rings (100=1 mm)	Difference in 2 yr. prior & post scar growth (%)	Sum of prior 20 rings (100=1 mm)	Sum of latter 20 rings (100=1mm)	Difference in 20 yr. prior & post scar growth (%)	Scar occurs	Season scar occurs	Interpretated cause of scar	Notes or Reference
Abernethy	Core	ABEA02	1.7	>0.5	0.2-0.3	?	0.65	263	207	-21%	772	556	-28%	1816	L	Mammal	
	Chronology	ABEA-16						172	164	-5%	1425	1762	24%				
	Chronology	ABEB-6						42	54	29%	514	452	-12%				
	Chronology	ABEC-20															Chronology starts 1938
Abernethy	Core	ABEA05	3.8	>0.5	0.2-0.3	N	0.28	33	28	-15%	475	252	-47%	*c.* 1887	?	Localised fire	Visable fire scar sampled
	Chronology	ABEA-16						114	145	27%	1327	1352	2%				
	Chronology	ABEB-6						130	146	12%	1152	1411	22%				
	Chronology	ABEC-20						138	202	46%	1355	1170	-14%				
Abernethy	Core	ABEA12	5.3	>0.5	0.2-0.3	N	0.39	64	44	-31%	691	748	8%	1920	E	Widespread fire	Visable fire scar sampled
	Chronology	ABEA-16						133	99	-26%	1285	1088	-15%				
	Chronology	ABEB-6						139	80	-42%	1359	849	-38%				
	Chronology	ABEC-20						75	78	4%	866	808	-7%				
Eilean Subhainn	Core	ESDB13	6.6	>0.5	0.63	S	1.04	134	197	47%	2208	1739	-21%	1961	L	Widespread fire	
	Chronology	ESDB-12						124	98	-21%	1545	812	-47%				
	Chronology	ESBE-9						175	140	-20%	1773	1575	-11%				
Eilean Subhainn	Core	ESDB07	12.6	>0.5	0.80		0.72	289	58	-80%	2242	1395	-38%	1923	?	Widespread fire	
	Chronology	ESDB-12						314	177	-44%	2656	1769	-33%				
	Chronology	ESBE-9						140	67	-52%	1618	924	-43%				
Loch Assynt	Section	ASSA03	1.8	0.3	0.41	NW	0.58	92	101	10%	691	1459	111%	*c.* RY92	E	Mammal	
	Chronology	ASSA-4						204	189	-7%	2083	1515	-27%				
Loch Assynt	Section	ASSA03	2.7	0.4	0.41	W	0.58	101	122	21%	1227	2027	65%	*c.* RY95	?	Mammal	
	Chronology	ASSA-4						189	151	-20%	2029	1494	-26%				
Loch Assynt	Section	ASSA03	14.5	2.2	0.41	SW	0.58	56	39	-30%	3279	1071	-67%	RY133	E	Localised fire	Scared through 0.13 m section
	Chronology	ASSA-4						271	280	3%	1919	1986	3%				
Polla on Loch Eriboll	Section	POLL05	4.6	0.8	0.65	W	0.62	133	81	-39%	1242	1021	-18%	RY83	?	Localised fire	Not evident at 0.60 m
	Chronology	POLL-6						194	135	-30%	1947	1801	-7%				
Polla on Loch Eriboll	Section	POLL05	5.0	1.8	0.60	NW	0.62	87	102	17%	1459	827	-43%	RY100	?	Localised fire	Not evident at 0.65 m
	Chronology	POLL-6						205	200	-2%	1755	1571	-10%				
Druim Bad a' Ghaill	Section	BADA08	13.5	2.5	0.10	NE	1.47	472	451	-4%	4726	3522	-25%	Ring 32	E	Fire	Not evident at 0.14 m

Underlined = indicates less than 20 rings available for calculation, E = earlywood, L = Latewood, ? = uncertain

Four subfossil samples show reductions in ring widths (ranging from 18-67% over a 20 year period) and three (ranging from 4-39% over a 2 year period) following scars. The scars in these samples are interpreted as caused by fire. Slight reductions in the site chronologies over both 2 and 20 year periods at this time are considered indicative that these fires were probably not widespread over the peat.

One scar in a modern bog pine sample (ABEA02) from Abernethy, and two scars in a subfossil sample (ASSA03) from Assynt, occur when the trees are under 3.8 cm in diameter and therefore these scars are considered likely to have been caused by mammals. The modern pine interpreted with a mammal scar show reductions of ring width over 20% over both the 2 and 20 years periods following the scar, both subfossil pine show increases over both periods. Therefore, no consistent growth response subsequent to mammal scarring is apparent.

3.3.8 Asymmetric growth in tree-rings and roots

The results of the orientation analysis on tree-ring and roots are summarised in Table 12 and shown graphically in Appendix II. From Modern Scots pine, 165 cores and 8 sections were recorded with orientation information from 18 sites. Of these, 67% had a difference between the maximum and opposite radii of ≥10%, which was the arbitrary level taken to be significant. Sites B, C and D at Abernethy, and sites A and B at Pithmaduthy, all sampled by north and south orientated cores, produce ambiguous results from which no prevailing wind direction could be interpreted. Twelve modern pine sites have a mean difference between the maximum and minimum radii of 24%, ranging from 18% to 35%, and these were used to interpret prevailing wind directions. No information was gathered on the orientation of modern pine roots.

Windthrown trees were recorded at Borgie, Eilann Subhainn – C, Strathnaver – B and near to Achanalt, which suggests that the trees at these sites might be susceptible to stress from wind. On Eilean Sùbhainn at site C, sample ESDG01 was east/west cored to within 5 years of pith from a tree windthrown by a westerly wind. The east core measured 127 mm; the west 150mm, this difference is recorded as 15% reduction (i.e. -15%) in radial growth on the east side. Seven cores recorded differences ≥ than a 10% between the lengths of opposite cores. The mean orientation of maximum radial growth for trees at this site is WSW. In the UK, the prevailing winds are from the west or south-west, therefore the mean orientation of maximum radial growth occurs in the lee of the prevailing wind, which is in agreement with Bannan and Bindra (1970) and Hamilton (2002). Furthermore, the mean maximum radial growth is orientated to the lee of four windthrown trees observed at this site. Four trees from the site were recorded with a difference of less than 10% between the length of the cores and these orientations were not used. One sample could not be cross-matched. Sites A and B on Eilean Sùbhainn are only slightly further inland but considerably more sheltered by the surrounding topography. The mean orientation of maximum radial growth at sites A and B infers prevailing wind from the NW and NNW respectively, which corresponds with the orientation of the loch.

At Strathnaver site C, five trees were recorded windthrown by a south-west wind and one by a westerly wind. The mean orientation of maximum radial growth at sites A and C occurs to the SSW and SW respectively, thus inferring a prevailing wind from these directions. Eight trees sampled from site B produced only 3 samples with differences greater than 10% and these were orientated in different directions. At Borgie Forest, three trees were recorded windthrown by SW, SE and ESE winds. The mean orientation of maximum radial growth at Borgie Forest is SSW. Achanalt was the only site where full sections were available. The mean orientation of maximum radial growth at Achanalt is SW, which corresponds to the direction of windthrow of a tree near to the site (Figure 28).

The mean orientation of maximum radial growth at Inshraich, sites A and B, infers prevailing winds from the SSW and south, respectively. The mean orientation of maximum radial growth at Monadh Mor, chronologies A and B, infer prevailing winds from the SW and north, respectively. The mean orientation of maximum radial growth at Abernethy chronology A infers a prevailing wind from the south.

Six subfossil pine sites produced 46 sections with orientation information. These sites have a mean difference between the maximum and minimum radii of 41%, ranging from 35% to 57%, and all were used to infer prevailing wind directions. None of the subfossil pine that cross-match in the WRATH-9 chronology were from windthrown trunks. However, seventeen samples had information on the orientation of their largest root recorded. At Polla on Loch Eriboll the mean orientation of maximum radial growth is to the SW, inferring that the prevailing wind came from the NE. At Strath Kanaird the mean orientation of maximum radial growth is to the SE, inferring that the prevailing wind came from the NW. At Loch Assynt the mean orientation of maximum radial growth infers a prevailing wind from the north. At Druim Bad a' Ghaill, Loch an Ruathair and a single sample from Loch Ascaig (sites all within 1 km of each other) the mean orientation of maximum radial growth infers prevailing winds from the NNW, WNW and NW, respectively. The mean orientations of maximum radial growth of samples from Polla on Loch Eriboll infer a NE prevailing wind. Polla on Loch Eriboll is at the head of a long SW/NE orientated loch which is likely to funnel any northerly wind in a NE direction. The orientation of largest root coincides with the mean orientation of maximum distance to pith at Druim Bad a' Ghaill, but opposes at Strath Kanaird and Loch Assynt. Orientation information from two chronologies developed at Druim Bad a' Ghaill which could not be cross-matched in the WRATH-9 chronology are also recorded in Table 12.

Table 12: Summary of orientation data for direction of minimum radial growth and roots

Period	Site name	Chronology	Substrate	Samples	Mean orientation of largest root	Mean orientation of maximum distance to pith	Mean % difference between maximum and opposing distance to pith	Samples with orientation data (roots)	Samples with a difference >= 10%	% of samples with a difference >= 10%	Infered direction of prevailing wind/paleo-wind	Notes
Modern	Abernethy - A	ABEA-16	Peat	Core		N	-35%	14	9	64%	S	
Modern	Abernethy - B	ABEB-6	Peat	Core		34% N & 66% S	-23%	4	3	75%	?	
Modern	Abernethy - C	ABEC-21	Peat	Core		40% N & 60% S	-22%	20	15	75%	?	
Modern	Abernethy - D	ABED-9	Mineral	Core		60% N & 40% S	-22%	11	7	64%	?	
Modern	Achanalt	ACHA-7	Mineral	Section		NE	-32%	8	7	88%	SW	Windblow tree = 1 to SW. Strath Bran WSW orientated
Modern	Borgie Forest	BODG-9	Mineral	Core		NNE	-20%	10	6	60%	SSW	Windthrown trees 1 to NE, 1 to SE, 1 to ESE
Modern	Eilann Subhainn - A	ESBE-9	Peat	Core		SE	-22%	9	8	89%	NW	Loch Maree on a NW/SE orientation
Modern	Eilann Subhainn - B	ESDB-12	Peat	Core		SSE	-25%	10	7	70%	NNW	Site on a down slope margin of bog
Modern	Eilann Subhainn - C	ESDG-13	Mineral	Core		ENE	-18%	12	8	67%	WSW	Windthrown trees = 3 to E
Modern	Inshriach - A	INSH-M1	Peat	Core		90% N & 10% S	-22%	11	9	82%	SSW	
Modern	Inshriach - B	INSH-M2	Mineral	Core		N	-30%	6	4	67%	S	
Modern	Monadh Mor - A	MOHM-M1	Peat	Core		80% N & 20% S	-24%	8	5	63%	SW	
Modern	Monadh Mor - B	MOHM-M2	Peat	Core		S	-23%	5	3	60%	N	
Modern	Pithmaduthy - A	PITM-M1	Peat	Core		50% N & 50% S	-30%	12	8	67%	?	
Modern	Pithmaduthy - B	PITM-M2	Mineral	Core		34% N & 66% S	-15%	5	3	60%	?	
Modern	Strathnaver - A	STPE	Peat	Core		NNE	-20%	10	6	60%	SSW	Windblown trees 5 to NE, 1 to E
Modern	Strathnaver - B	STWB-6	Peat	Core		Varied	-27%	8	3	38%	?	Sites A, B & C orientation as Loch Naver
Modern	Strathnaver - C	STIN-7	Mineral	Core		NE	-16%	10	5	50%	SW	
Neolithic	Druim Bad a' Ghaill	BADA-12	Peat	Section	ESE	SSE	-35%	12 (5)	12	100%	NNW	unmatched = 2 trunks windthrown to NNE, 1 to S
Holocene	Druim Bad a' Ghaill	BADA-B	Peat	Section	NE	ENE	-29%	6 (4)	6	100%	WSW	
Holocene	Druim Bad a' Ghaill	BADA-C	Peat	Section	ENE	ENE	-25%	2 (2)	2	100%	WSW	
Neolithic	Loch an Ruathair	RATH-8	Peat	Section	NNE	ESE	-38%	7 (2)	7	100%	WNW	
Neolithic	Loch Ascaig	ASCA-3	Peat	Section		SE	-36%	1	1	100%	NW	
Neolithic	Loch Assynt	ASSA-4	Peat	Section	N	S	-34%	4 (3)	4	100%	N	unmatched = 2 trunks windthrown to SW + 1 root W
Neolithic	Polla on Loch Eriboll	POLL-6	Peat	Section		SE	-57%	4	4	100%	NE	unmatched = 1 root to E, 1 to S, 1 to NW
Neolithic	Strath Kanaird	SMUR-13	Peat	Section	NE	SE	-45%	10 (1)	10	100%	NE	unmatched = 2 roots to NE, 1 to NNE, 1 to NNW, 1 to E, 1 to WNW, 1 to WSW

Key: N = north; E = east; S = south; W = west; ? = no wind direction inferred. Grey denotes modern sites from which interpretation was unclear and subfossil pine chronologies which were not cross-matched in the WRATH-9 chronology

3.4 Climate Analysis of Scots pine

3.4.1 Comparisons of standardisation methods

The statistics of the chronologies calculated from the three methods of standardization used allow the effects of different standardization methods to be assessed (Table 13). It is readily apparent that many of the statistics are extremely similar regardless of the method of standardisation. A total of 30 chronologies were standardised, on average containing 11 trees. Wigley *et al*. (1984) suggest an expressed population signal (EPS) threshold of 0.85 as constituting a reasonably threshold of acceptable statistical quality. The EPS varied only slightly between the three detrending methods, but method 3 generally increased this value. Overall the chronologies developed by method 3 had a mean EPS value of 0.84, ranging from 0.70 to 0.93 in chronologies developed from 9 trees and 15 trees, respectively. Chronologies with only moderately high EPS values may still be highly correlated with climatic parameters. An unexpectedly high number of tree-ring sequences failed to display a normal growth trend and therefore the percentage of trees from each site with expected growth trend were calculated and recorded with the more usual statistics (Table 13). With the exception of MONM-M1, all the peat sites sampled contained trees without normal growth trend, this ranged from 11 to 100%. The upland area of the Cairngorms also appears susceptible to the absence of growth trend, affecting between 56 to 80% of trees sampled from these sites.

The greatest differences between the three standardisation methods are seen in R1 (serial autocorrelation) and PC1. Standardisation for all correlation function and response function analysis was achived by using a negative exponential curve/linear regression, followed by a 20 year spline (see detrending method 3 in section 2.1.7) through the ARSTAN program {Holmes, Adams, et al. 1986 HOLMES1986 /id} and the residual chronologies used. R1 is reduced to minimal levels in all but three of the residual chronologies used for climatic analysis, the exceptions being PITM-M1, MONM-M1 and GLNDERRY.

3.4.2 Stable relationships between climate and ring width

The relationship of ring width with temperature, rainfall and the NAO index were examined by correlation function and response functions over a 12 month window (Table 14). Comparison of correlation of tree-ring data with mean, minimum and maximum temperatures identified little difference in the relationship to these three variables (Table 15). Bootstrap response functions were found to identify similar but slightly lower significance relationships with climate data than bootstrap correlation functions and therefore the latter were used. Strength of relationships with climate variables in correlation functions could often be increased by using base lengths less than the 80 year used in this analysis, but often at a loss of stability of response.

The data from climate stations were mostly of sufficient length to enable moving correlation functions to be performed for rainfall, temperature and NAO Index. Both the NAO indices of Hurrell (1995) and Luterbacher (1999) were compared in analysis. Hurrell's data generally gave slightly stronger correlations (results not shown) and therefore this data set was used, these indices are based on the difference of normalized sea level pressure between Ponta Delgada (Azores) and Stykkishoimur/Reykjavik (Iceland), since 1865. Due to the short length of records for sunshine at most sites, this climatic factor was not investigated. The results of the moving correlation functions are recorded as charts (Appendix X); on these the period used for Correlation analysis (1881-1960) is identified to help comparisons. When interpreting moving response charts it should be recognised that stable and ephemeral relationships between tree-rings and climate data are relative to the total period analysed and therefore subjective.

Table 13: Tree-ring chronology statistics after standardization using detrending methods 1,2 or 3, using ARSTAN

Raw data:									**Standardised chronology**												**Reisidual chronology**			
Chronology Name	Site type	Mean length	*n* trees	MR	SD	Range (AD)	Length	Trees with expected growth trend	SD	Skew	Kurtosis	MS	R1	PC1	Rbar	Optimum common interval	SNR	EPS	Number of cores to exceed SSS of 0.85	SD of index	MS	R1	Detrend-ing method
BODG-09	Mineral	39	9	2.82	1.78	1964-2005	42	100%	0.22	1.08	6.55	0.17	0.34	11%	0.41	1969-2002	6.15	0.86	4	0.18	0.20	0.00	1
									0.18	-0.13	4.50	0.18	0.31	9%	0.44		7.07	0.88	4	0.16	0.18	0.05	2
									0.18	0.01	4.72	0.18	0.25	6%	0.44		7.22	0.88	4	0.16	0.18	0.05	3
STWB-13	Mineral	36	13	2.31	1.65	1965-2005	41	100%	0.28	0.90	4.61	0.19	0.81	45%	0.46	1975-2001	9.35	0.90	5	0.19	0.20	0.12	1
									0.24	0.72	3.49	0.19	0.68	34%	0.50		11.30	0.92	4	0.19	0.19	0.09	2
									0.22	0.71	3.80	0.20	0.64	31%	0.50		11.69	0.92	4	0.18	0.19	0.07	3
ESBE-09	Peat	83	9	0.87	0.49	1869-2005	137	89%	0.29	-0.07	2.60	0.20	0.57	33%	0.32	1901-1968	2.43	0.71	4	0.23	0.25	0.03	1
									0.26	-0.09	2.60	0.20	0.46	21%	0.32		2.52	0.72	4	0.23	0.24	0.05	2
									0.20	0.36	3.75	0.21	0.12	11%	0.31		2.36	0.70	4	0.19	0.21	-0.08	3
ESDB-12	Peat	144	12	0.86	0.51	1790-2005	216	75%	0.33	0.50	2.76	0.20	0.78	61%	0.37	1882-1974	5.88	0.86	5	0.21	0.24	-0.10	1
									0.31	0.72	3.68	0.12	0.69	47%	0.37		5.75	0.85	5	0.22	0.24	-0.07	2
									0.20	0.44	3.63	0.19	0.44	17%	0.37		5.96	0.86	5	0.19	0.21	0.01	3
ESDG-13	Mineral	105	13	1.19	0.84	1837-2005	169	100%	0.36	-0.16	3.01	0.22	0.59	56%	0.28	1882-1969	1.76	0.64	4	0.19	0.20	0.11	1
									0.27	-0.50	3.29	0.21	0.49	24%	0.27		2.53	0.72	5	0.19	0.21	0.01	2
									0.20	-0.03	4.41	0.19	0.11	8%	0.37		2.90	0.74	5	0.18	0.20	-0.01	3
LCHMAREE	Mineral	168	8	1.47	0.73	1756-1978	223	100%	0.20	0.08	2.74	0.16	0.61	47%	0.32	1845-1978	4.67	0.82	4	0.16	0.18	**-0.11**	1
									0.19	0.68	4.30	0.16	0.58	33%	0.32		4.82	0.83	4	0.17	0.18	**-0.13**	2
									0.15	0.33	3.35	0.14	0.31	10%	0.32		4.97	0.83	4	0.14	0.16	-0.01	3
BNAA-10	Mineral	140	10	1.10	0.52	1809-1989	181	100%	0.19	-0.29	3.13	0.17	0.49	31%	0.24	1869-1979	2.64	0.73	5	0.16	0.19	-0.06	1
									0.17	-0.23	3.18	0.16	0.44	19%	0.25		2.80	0.74	4	0.16	0.19	-0.09	2
									0.15	-0.09	2.82	0.16	0.05	21%	0.26		2.75	0.73	5	0.14	0.15	-0.10	3
COULIN	Mineral	228	11	1.06	0.60	1671-1978	308	100%	0.22	0.78	5.16	0.14	0.66	44%	0.29	1833-1978	4.74	0.83	5	0.14	0.16	0.01	1
									0.21	0.53	4.05	0.13	0.62	38%	0.29		5.04	0.83	5	0.14	0.15	0.06	2
									0.14	0.39	4.98	0.12	0.29	22%	0.32		5.90	0.86	5	0.12	0.13	0.10	3
ACHA-07	Mineral	111	7	1.79	0.96	1893-2004	112	43%	0.29	0.42	3.09	0.18	0.75	56%	0.33	1895-2004	3.49	0.78	4	0.19	0.21	0.00	1
									0.24	0.64	3.38	0.19	0.62	38%	0.35		3.77	0.79	4	0.19	0.21	0.06	2
									0.19	0.48	3.51	0.18	0.35	25%	0.38		4.24	0.81	4	0.16	0.18	0.02	3
SHIELDDAG	Mineral	111	11	1.92	0.81	1847-1978	132	100%	0.19	0.19	3.89	0.12	0.74	55%	0.37	1883-1967	7.82	0.89	4	0.13	0.16	0.00	1
									0.18	-0.17	3.51	0.12	0.70	49%	0.38		7.85	0.89	4	0.13	0.15	-0.02	2
									0.13	-0.21	3.34	0.12	0.47	32%	0.34		6.05	0.86	5	0.11	0.12	-0.03	3
PLOCKTON	Mineral	84	12	2.23	1.15	1879-1976	98	100%	0.20	1.20	5.47	0.13	0.64	41%	0.42	1909-1976	8.92	0.90	5	0.15	0.17	-0.04	1
									0.15	0.23	2.87	0.13	0.49	24%	0.38		7.73	0.89	5	0.13	0.15	-0.05	2
									0.12	0.11	2.81	0.12	0.38	13%	0.39		7.58	0.88	5	0.12	0.14	-0.13	3
MALLAIG	Mineral	59	10	3.38	1.24	1903-1976	74	90%	0.17	-0.23	3.41	0.14	0.88	48%	0.27	1931-1972	3.91	0.80	6	0.12	0.14	0.04	1
									0.15	-0.57	3.45	0.13	0.82	42%	0.31		4.44	0.82	6	0.12	0.13	0.11	2
									0.13	-0.80	3.94	0.12	0.69	35%	0.34		5.04	0.83	5	0.11	0.12	0.10	3
GLNAFRIC	Mineral	187	13	1.12	0.50	1735-1976	242	62%	0.31	-0.02	2.62	0.15	0.65	72%	0.31	1827-1976	5.56	0.85	6	0.16	0.17	-0.18	1
									0.31	2.00	12.30	0.14	0.63	39%	0.29		5.35	0.84	6	0.19	0.19	-0.22	2
									0.14	1.18	13.14	0.12	0.21	10%	0.30		5.27	0.84	6	0.14	0.14	-0.15	3
PITM-M2	Mineral	58	6	2.41	1.13	1938-1999	62	33%	0.38	-0.01	2.23	0.22	0.84	70%	0.37	1949-1991	3.62	0.78	4	0.18	0.20	-0.06	1
									0.23	0.14	3.27	0.19	0.52	27%	0.42		4.77	0.83	3	0.19	0.21	-0.01	2
									0.18	0.12	3.03	0.19	0.24	10%	0.38		3.97	0.80	4	0.17	0.19	-0.06	3
PITM-M1	Peat	77	12	0.79	0.51	1875-1999	125	58%	0.46	2.18	10.87	0.22	1.05	61%	0.47	1923-1999	5.48	0.85	6	0.26	0.23	**0.20**	1
									0.39	2.83	16.85	0.21	0.99	54%	0.47		5.61	0.85	6	0.25	0.23	**0.18**	2
									0.25	1.81	12.41	0.19	0.63	35%	0.35		5.84	0.85	5	0.20	0.12	**0.14**	3
MONM-M1	Peat	86	6	1.59	0.72	1909-1999	94	100%	0.21	-0.02	2.89	0.16	0.67	35%	0.34	1922-1999	3.24	0.76	4	0.16	0.17	**0.14**	1
									0.21	0.31	3.47	0.16	0.60	28%	0.35		3.49	0.78	4	0.16	0.16	**0.20**	2
									0.16	-0.13	2.74	0.16	0.49	22%	0.38		3.86	0.79	4	0.14	0.15	**0.11**	3
ABEA-16	Peat	155	16	0.61	0.30	1798-2000	203	75%	0.24	0.40	4.32	0.18	0.61	37%	0.26	1871-2000	4.43	0.82	8	0.18	0.21	0.03	1
									0.24	0.33	4.26	0.18	0.57	33%	0.26		4.83	0.83	7	0.19	0.20	0.08	2
									0.20	0.34	5.40	0.17	0.27	22%	0.29		5.22	0.84	7	0.16	0.17	0.07	3
ABEB-06	Peat	156	6	0.76	0.39	1694-2000	130	0%	0.36	0.96	4.02	0.23	0.84	71%	0.35	1880-2000	3.06	0.75	3	0.21	0.25	-0.11	1
									0.30	0.34	2.92	0.22	0.65	42%	0.35		2.98	0.76	3	0.24	0.28	-0.07	2
									0.23	0.49	4.53	0.21	0.31	25%	0.35		2.61	0.72	4	0.20	0.21	0.01	3
ABEC-21	Peat	123	21	0.64	0.34	1856-2000	145	48%	0.35	0.26	2.52	0.19	0.81	66%	0.38	1871-1999	8.52	0.90	6	0.21	0.23	0.06	1
									0.24	0.40	3.12	0.18	0.72	39%	0.34		7.34	0.88	6	0.19	0.21	0.07	2
									0.19	0.12	3.12	0.18	0.40	31%	0.32		7.19	0.88	6	0.16	0.18	0.04	3
CFF-11	Mineral	96	11	1.59	0.69	1880-1979	100	73%	0.16	-0.42	3.51	0.13	0.60	29%	0.27	1896-1978	3.65	0.79	7	0.13	0.15	0.02	1
									0.14	-0.69	4.50	0.13	0.48	21%	0.22		3.15	0.76	7	0.13	0.14	-0.02	2
									0.13	-1.01	5.05	0.13	0.25	20%	0.24		2.83	0.74	7	0.11	0.12	-0.03	3
ABED-09	Mineral	64	9	1.78	0.60	1882-2000	119	56%	0.38	1.08	6.33	0.18	0.40	16%	0.27	1955-2000	3.62	0.78	5	0.20	0.20	0.19	1
									0.31	0.57	5.07	0.18	0.35	15%	0.23		3.07	0.75	6	0.19	0.19	0.10	2
									0.20	-0.44	5.12	0.17	0.12	17%	0.24		3.06	0.75	6	0.17	0.18	0.08	3
CFG-13	Mineral	94	13	1.44	0.71	1880-1979	100	100%	0.22	0.44	3.85	0.13	0.63	40%	0.39	1896-1976	8.23	0.89	5	0.16	0.17	-0.03	1
									0.18	-0.07	2.85	0.13	0.55	30%	0.40		8.52	0.90	5	0.14	0.16	-0.06	2
									0.12	-0.07	3.63	0.13	0.20	4%	0.38		7.89	0.89	7	0.12	0.14	-0.03	3
CFE-11	Mineral	100	9	0.72	0.27	1880-1979	100	44%	0.20	0.49	4.51	0.17	0.46	31%	0.30	1880-1979	3.89	0.80	5	0.17	0.20	-0.08	1
									0.18	0.52	3.73	0.17	0.41	17%	0.31		4.05	0.80	5	0.16	0.19	-0.12	2
									0.15	0.53	4.40	0.15	0.18	3%	0.34		4.62	0.82	5	0.14	0.16	0.01	3
CFD-11	Mineral	100	11	0.49	0.17	1880-1979	100	36%	0.24	0.30	2.90	0.16	0.51	44%	0.51	1880-1979	11.49	0.92	4	0.17	0.21	0.00	1
									0.21	0.49	4.36	0.16	0.37	24%	0.53		12.58	0.93	4	0.17	0.20	-0.09	2
									0.15	0.11	3.39	0.16	0.17	3%	0.51		11.45	0.92	4	0.15	0.18	-0.07	3
CFA-15	Mineral	100	15	1.09	0.31	1880-1979	100	33%	0.17	0.24	3.48	0.14	0.54	29%	0.46	1880-1979	12.65	0.93	5	0.14	0.16	-0.06	1
									0.15	0.40	3.78	0.14	0.38	15%	0.47		13.23	0.93	5	0.14	0.16	-0.03	2
									0.13	0.04	3.48	0.13	0.15	15%	0.46		12.90	0.93	5	0.12	0.13	-0.10	3
CFB-10	Mineral	95	10	1.03	0.36	1880-1979	100	20%	0.23	0.49	3.55	0.15	0.68	46%	0.43	1885-1979	7.66	0.89	4	0.16	0.18	-0.01	1
									0.20	0.47	4.10	0.15	0.51	26%	0.42		7.13	0.88	5	0.16	0.17	-0.03	2
									0.16	-0.22	4.00	0.15	0.33	16%	0.44		7.04	0.88	5	0.14	0.16	-0.08	3
GLNDERRY	Mineral	179	13	1.28	0.59	1773-1978	206	100%	0.15	0.23	3.59	0.13	0.44	20%	0.40	1833-1978	8.92	0.89	5	0.13	0.16	**-0.20**	1
									0.14	0.04	3.21	0.13	0.39	15%	0.40		8.17	0.89	5	0.13	0.16	**-0.17**	2
									0.12	-0.08	3.12	0.13	0.09	12%	0.42		8.77	0.90	5	0.11	0.13	**-0.16**	3
INVEREY	Mineral	236	12	1.14	0.64	1706-1976	271	100%	0.21	0.48	3.64	0.13	0.76	57%	0.40	1783-1976	7.94	0.89	5	0.14	0.16	-0.04	1
									0.19	0.33	3.46	0.12	0.72	52%	0.40		8.00	0.89	5	0.14	0.16	-0.01	2
									0.13	0.17	3.13	0.12	0.25	36%	0.37		6.93	0.87	5	0.10	0.12	-0.07	3
BALLOCHB	Mineral	230	11	1.32	0.67	1712-1978	267	100%	0.17	0.51	3.78	0.13	0.56	31%	0.34	1770-1978	5.57	0.85	5	0.17	0.17	-0.15	1
									0.16	0.42	3.19	0.13	0.51	26%	0.35		5.70	0.85	5	0.14	0.16	**-0.14**	2
									0.13	0.35	2.94	0.13	0.26	16%	0.36		5.96	0.86	5	0.11	0.14	-0.07	3
DIMMIE	Mineral	132	12	1.73	0.84	1828-1976	149	83%	0.27	-0.15	3.09	0.17	0.74	55%	0.39	1854-1974	7.74	0.89	5	0.18	0.20	-0.02	1
									0.24	-0.21	4.04	0.17	0.61	37%	0.39		7.28	0.88	5	0.18	0.20	0.01	2
									0.18	-0.69	4.59	0.15	0.47	24%	0.38		7.30	0.88	5	0.15	0.17	-0.07	3

KEY: 🟨 = Peat site type, MR = mean ring-width (mm/yr), SD = standard diviation, MS = mean sensitivity, R1 = serial autocorrelation.
RBar = mean correlation among trees for the common overlap period.
SNR = signal to noise ratio, EPS = expressed population signal, SSS = subsample signal strength

Correlation and moving correlation functions identify the common response of Scots pine to climate at eight mineral substrate sites ranging from 300-500 m in the Cairngorm Mountains. Temperature in January and February is consistently the most important determinant of ring width. July and/or August temperature is also important at all but the site over 550 m. These statistically significant correlations with temperature are positive and stable over time. Negative correlations with rainfall occur in August, suggesting that “poor” summers for tree growth are cool and wet, though this relationship is less stable and occurs in July at some sites. The response to January and February temperature on mineral substrate sites is widespread, evident at Dimme 90 km south and Glen Affric 70 km west (25 km beyond the Great Glen fault).

Three peat substrate Scots pine sites at Abernethy in the Cairngorms show North Atlantic Oscillation in May as the most important determinant of ring width. The moving response analysis indicates that this negative response becomes significant from the 1910s, and suggests strong westerlies have an adverse influence on ring-growth. Positive correlations with rainfall occur in June, with a corresponding negative response to temperature in the same month at two of the sites, suggesting cool and wet conditions in June promote tree growth.

Six mineral substrate Scots pine sites ranging from 12-300 m are clustered within 40 km of each other on the west coast of northern Scotland, but no common response to monthly temperature, rainfall or North Atlantic Oscillation was evident. Significant correlation of ring-width with temperature occurs in January at Loch Maree and Shieldaig, and in February at Beinn Eighe. These significant correlations with temperature were positive and stable over time. The Scots pine at these three sites also show positive and stable correlations with NAO indices in February at Beinn Eighe, from January to February at Loch Maree, and from December to February at Shieldaig. These results are consistent with strong winter westerlies increasing the warming influence of the Gulf Stream, resulting in warm wet late winters that favour tree-ring growth that occurs later in the year. Additionally in this west coast cluster, the Scots pine at Loch Maree, Beinn Eighe and Coulin show stable positive correlation with NAO indices in April and at Eilean Sùbhainn and Shieldaig they show stable positive correlation with temperature in October. Scots pine at Loch Maree also shows the positive correlation with temperature in October; however the relationship is not stable.

Also on the west coast of northern Scotland, two peat substrate Scots pine chronologies from 50 m altitude on Eilean Sùbhainn show stable positive correlation with temperature in October and NAO indices in February. As already described, these two relationships are each identified at three of the mineral substrate Scots pine sites in this cluster and suggest these climatic factors influence Scots pine on both peat and mineral substrate across this region. Interestingly a positive correlation with temperature in October is the only common relationship identified at the two remaining peat substrate Scots pine sites located near Inverness on the east coast of Scotland. The Scots pine growing at Glen Affric have already been identified to show the January and February temperature correlations common to the Cairngorm cluster of sites (see above). However, this site also clearly demonstrates a positive and stable correlation with NAO indices in January and February, a correlation which is identified in some of the west coast cluster of pine. A positive and stable correlation with NAO indices in February is also evident in three of the Cairngorm cluster of Scots pine sites and one of the sites at Abernethy where pine grows on a peat substrate. The correlation of ring growth with February NAO indices at 10 sites suggests that the influence is regional, but more evident at some sites particularly those on the west coast.

Table 14: Correlation analysis of tree-ring data with three monthly climatic variables, over a common interval 1881 to 1960

Climate data	Analysis	Relative Location	Pine Chronology Brief Description	Selected Interval (years)	Temperature (Mean)												Precipitation												North Atlantic Oscillation (Hurrell 1995)											
					DEC-T	Jan-T	Feb-T	Mar-T	Apr-T	May-T	Jun-T	Jul-T	Aug-T	Sep-T	Oct-T	Nov-T	DEC-P	Jan-P	Feb-P	Mar-P	Apr-P	May-P	Jun-P	Jul-P	Aug-P	Sep-P	Oct-P	Nov-P	DEC-O	Jan-O	Feb-O	Mar-O	Apr-O	May-O	Jun-O	Jul-O	Aug-O	Sep-O	Oct-O	Nov-O
		North west	Total occurences of correlation		0	3	3	1	1	0	0	2	1	0	5	1	0	3	4	2	1	1	0	0	1	0	0	0	1	4	6	2	4	0	2	0	1	0	2	2
		South east	Total occurences of correlation		2	10	11	5	3	0	4	6	8	2	2	2	0	0	2	0	2	0	5	1	8	2	0	2	2	4	4	1	4	5	0	1	2	0	2	1
SIT/Lairg	BCC	North west	BODG-9F - Borgie - 200m - Mineral	> 30 years																																				
SIT/Lairg	BCC	North west	STWB-13 - Strathnaver - 25m - Mineral	> 30 years																																				
SIT/Kinlochewe	BCC	North west	ESBE-09 - Eilean Subhainn - 50m - Peat	1881-1960 (80y)											0.21					0.25												0.22			0.20					0.27
SIT/Kinlochewe	BCC	North west	ESDB-12 - Eilean Subhainn - 50m - Peat	1881-1960 (80y)			0.22								0.30				0.25												0.32								0.24	
SIT/Kinlochewe	BCC	North west	ESDG-13 - Eilean Subhainn - 50m - Mineral	1881-1960 (80y)											0.21			0.23	0.25			0.33																	0.21	
SIT/Kinlochewe	BCC	North west	LCKMAREE - Loch Maree - 100mm - Mineral	1881-1960 (80y)		0.32						0.24			0.19			0.24												0.31	0.24		0.20							
SIT/Kinlochewe	BCC	North west	BNAA-10 - Beinn Eighe - 300m - Mineral	1881-1960 (80y)			0.23																							0.21	0.26		0.22							
SIT/Kinlochewe	BCC	North west	COULIN - Coulin - 250m - Mineral	1881-1960 (80y)								0.23	0.28			-0.31					0.24												0.26							-0.25
SIT/Kinlochewe	BCC	North west	ACHA-07 - Acanalt - 130m - Mineral	1894-1960 (67y)					0.27																															
SIT/Kinlochewe	BCC	North west	SHIELDAIG - Shieldaig - 12m - Mineral	1881-1960 (80y)		0.36		0.23							0.25			0.26	0.37	0.24									0.32	0.34	0.28	0.21								
SIT/Kinlochewe	BCC	North west	PLOCKTON - Plockton - 100m - Mineral	1881-1960 (80y)																					-0.21															
SIT/Kinlochewe	BCC	North west	MALLAIG - Mallaig - 100m - Mineral	1904-1960 (57y)																																				
SIT/Kinlochewe	BCC	North west	GLNAFRIC - Glen Affric - 300m - Mineral	1881-1960 (80y)		0.34	0.23												0.25											0.31	0.35		0.27				0.21			
SMT/Inverness	BCC	South east	PITM-M2 - Pitmaduthy - 100m - Mineral	> 30 years																																				
SMT/Inverness	BCC	South east	PITM-M1 - Pitmaduthy - 100m - Peat	1881-1960 (80y)	0.25				0.24		0.16				0.33													-0.21	0.24								-0.22			
SMT/Inverness	BCC	South east	MONM-M1 - Monadh Mor - 200m - Peat	1907-1960 (54y)									0.40	0.29	0.30																		0.24							
SMT/Braemar	BCC	South east	ABEA-16 - Abernethy - 300m - Peat	1881-1960 (80y)																			0.24										0.22	-0.33						
SMT/Braemar	BCC	South east	ABEB-06 - Abernethy - 300m - Peat	1881-1960 (80y)							-0.21												0.26								0.24		0.19	-0.26						
SMT/Braemar	BCC	South east	ABEC-21 - Abernethy 300m - Peat	1881-1960 (80y)							-0.27												0.29											-0.29						
SMT/Braemar	BCC	South east	ABED-09 - Abernethy - 300m - Mineral	1883-1960 (78y)		0.20	0.28						0.28													0.24					0.29			-0.19					0.24	
SMT/Braemar	BCC	South east	CFG-13 - Carrbridge - 270m - Mineral	1881-1960 (80y)			0.23						0.18	0.32									0.30							0.22				-0.22						
SMT/Braemar	BCC	South east	CFF-11 - Creag Fhiaclach - 280m - Mineral	1881-1960 (80y)		0.30	0.31	0.27					0.20										0.28		-0.20														0.28	
SMT/Braemar	BCC	South east	CFE-09 - Creag Fhiaclach - 400m - Mineral	1881-1960 (80y)	0.24	0.39	0.23	0.22				0.41	0.26								0.25			-0.24	-0.27				0.23	0.25										
SMT/Braemar	BCC	South east	CFD-11 - Creag Fhiaclach - 450m - Mineral	1881-1960 (80y)		0.32	0.32					0.29									0.18				-0.20					0.27										
SMT/Braemar	BCC	South east	CFA-15 - Creag Fhiaclach - 500m - Mineral	1881-1960 (80y)		0.29	0.31	0.17				0.23													-0.28	-0.19														
SMT/Braemar	BCC	South east	CFB-10 - Creag Fhiaclach - 550m - Mineral	1881-1960 (80y)		0.27	0.31												-0.20						-0.23															
SMT/Braemar	BCC	South east	GLENDERRY - Glen Derry - 400m - Mineral	1881-1960 (80y)		0.27	0.22		0.22			0.29	0.44			-0.29			0.24						-0.31						0.28		0.21				0.25			-0.27
SMT/Braemar	BCC	South east	INVEREY - Inverey - 500m - Mineral	1881-1960 (80y)		0.25	0.24		0.23		0.24	0.35	0.27			-0.33									-0.32			0.22								-0.28				
SMT/Braemar	BCC	South east	BALLOCHB - Ballochbuite - 380m - Mineral	1881-1960 (80y)		0.23	0.32	0.30				0.22	0.22												-0.21					0.27										
SMT/Edinburgh	BCC	South east	DIMMIE - Dimmie - 200m - Mineral	1881-1960 (80y)		0.23	0.35	0.31																							0.26	0.24								

KEY: Underlined = significant response function relationship, red = EPS < 0.85

☐ = Mineral 🟨 = Peat ▨ = no analysis 🟦 🟧 🟩 = Predominantly stable relationship from moving correlation analysis

Table 15: Correlation analysis of tree-ring data with mean, minimum and maximum temperature, for common interval 1881 to 1960

			Temperature (Mean)												Temperature (Min)												Temperature (Max)											
Relative Location	Pine Chronology Brief Description	Selected Interval (years)	DEC-T	Jan-T	Feb-T	Mar-T	Apr-T	May-T	Jun-T	Jul-T	Aug-T	Sep-T	Oct-T	Nov-T	DEC-P	Jan-P	Feb-P	Mar-P	Apr-P	May-P	Jun-P	Jul-P	Aug-P	Sep-P	Oct-P	Nov-P	DEC-O	Jan-O	Feb-O	Mar-O	Apr-O	May-O	Jun-O	Jul-O	Aug-O	Sep-O	Oct-O	Nov-O
North west	Total occurences of correlation		0	3	3	1	1	0	0	2	1	0	5	1	0	4	2	0	1	0	1	1	1	1	4	1	0	3	3	1	1	0	0	3	2	0	4	1
South east	Total occurences of correlation		2	10	11	5	3	0	4	6	8	2	2	2	3	10	10	4	4	1	5	3	5	1	2	2	1	9	8	5	2	0	1	8	8	2	2	2
North west	BODG-9F - Borgie - 200m - Mineral	> 30 years																																				
North west	STWB-13 - Strathnaver - 25m - Mineral	> 30 years																																				
North west	ESBE-09 - Eilean Subhainn - 50m - Peat	1881-1960 (80y)											0.21												0.20												0.20	
North west	ESDB-12 - Eilean Subhainn - 50m - Peat	1881-1960 (80y)			0.22								0.30			0.21								0.19	0.30				0.24								0.28	
North west	ESDG-13 - Eilean Subhainn - 50m - Mineral	1881-1960 (80y)											0.21																								0.22	
North west	LCKMAREE - Loch Maree - 100mm - Mineral	1881-1960 (80y)		0.32						0.24			0.19			0.31						0.19			0.20			0.31	0.22					0.30				
North west	BNAA-10 - Beinn Eighe - 300m - Mineral	1881-1960 (80y)			0.23												0.21												0.25					0.20	0.20			
North west	COULIN - Coulin - 250m - Mineral	1881-1960 (80y)								0.23	0.28			-0.31		0.22					0.22		0.28			-0.28								0.30	0.28			-0.34
North west	ACHA-07 - Acanalt - 130m - Mineral	1894-1960 (67y)					0.27												0.28												0.26							
North west	SHIELDAIG - Shieldaig - 12m - Mineral	1881-1960 (80y)		0.36		0.23							0.25			0.35									0.27			0.36		0.24							0.23	
North west	PLOCKTON - Plockton - 100m - Mineral	1881-1960 (80y)																																				
North west	MALLAIG - Mallaig - 100m - Mineral	1904-1960 (57y)																																				
North west	GLNAFRIC - Glen Affric - 300m - Mineral	1881-1960 (80y)		0.34	0.23											0.31	0.22											0.35	0.24									
South east	PITM-M2 - Pitmaduthy - 100m - Mineral	> 30 years																																				
South east	PITM-M1 - Pitmaduthy - 100m - Peat	1881-1960 (80y)	0.25				0.24		0.16				0.33		0.26				0.23						0.31		0.22				0.22						0.33	
South east	MONM-M1 - Monadh Mor - 200m - Peat	1907-1960 (54y)									0.40	0.29	0.30						0.32				0.37											0.33	0.38	0.32	0.33	
South east	ABEA-16 - Abernethy - 300m - Peat	1881-1960 (80y)																																				
South east	ABEB-06 - Abernethy - 300m - Peat	1881-1960 (80y)							-0.21												-0.20																	
South east	ABEC-21 - Abernethy 300m - Peat	1881-1960 (80y)							-0.27												-0.20				0.19								-0.26	-0.22				
South east	ABED-09 - Abernethy - 300m - Mineral	1883-1960 (78y)		0.20	0.28						0.28					0.19	0.29						0.25					0.20	0.26						0.26			
South east	CFG-13 - Carrbridge - 270m - Mineral	1881-1960 (80y)			0.23						0.18	0.32					0.23							0.25											0.16	0.34		
South east	CFF-11 - Creag Fhiaclach - 280m - Mineral	1881-1960 (80y)		0.30	0.31	0.27					0.20					0.30	0.32	0.23										0.30	0.29	0.27					0.21			
South east	CFE-09 - Creag Fhiaclach - 400m - Mineral	1881-1960 (80y)	0.24	0.39	0.23	0.22				0.41	0.26				0.23	0.39	0.23	0.22	0.27		0.23	0.27					0.24	0.38		0.21				0.45	0.29			
South east	CFD-11 - Creag Fhiaclach - 450m - Mineral	1881-1960 (80y)		0.32	0.32					0.29						0.32	0.31					0.24						0.32	0.31					0.27				
South east	CFA-15 - Creag Fhiaclach - 500m - Mineral	1881-1960 (80y)		0.29	0.31	0.17				0.23						0.29	0.32											0.29	0.30	0.20				0.28	0.17			
South east	CFB-10 - Creag Fhiaclach - 550m - Mineral	1881-1960 (80y)		0.27	0.31											0.26	0.26											0.26	0.29									
South east	GLENDERRY - Glen Derry - 400m - Mineral	1881-1960 (80y)		0.27	0.22		0.22			0.29	0.44			-0.29		0.28	0.26				0.23		0.38			-0.28		0.24			0.22			0.38	0.43			-0.28
South east	INVEREY - Inverey - 500m - Mineral	1881-1960 (80y)		0.25	0.24		0.23		0.24	0.35	0.27			-0.33	0.24	0.25			0.26	0.20	0.32	0.23	0.23			-0.31		0.25	0.23					0.38	0.29			-0.34
South east	BALLOCHB - Ballochbuite - 380m - Mineral	1881-1960 (80y)		0.23	0.32	0.30				0.22	0.22					0.23	0.34	0.26					0.23					0.23	0.29	0.31				0.22	0.19			
South east	DIMMIE - Dimmie - 200m - Mineral	1881-1960 (80y)		0.23	0.35	0.31										0.23	0.36	0.26											0.31	0.32								

KEY: Underlined = significant response function relationship, red = EPS > 0.85

☐ = Mineral 🟨 = Peat ▨ = >30y no analysis 🟧 = Predominantly stable relationship from moving response analysis

3.4.3 A change in the relationship of climate and ring width from the 1920s

Only four of the eleven chronologies of Scots pine growing on mineral substrate, which are clustered in the south-east area, are of sufficient length for moving correlation functions to show longer term changes in relationship between climate and ring width before the 1920s. Nevertheless, Scots pine at all four sites (Glen Derry, Inverey, Ballochbuite and Dimmie) show the correlations with January temperature to cease in the 1920s and two sites (Inverey, Ballochbuite) show correlations with February temperature to cease in the 1920s. Despite the moving correlation functions of Scots pine growing at Carrbridge and Creag Fhiaclach only extending from 1920 it is interesting to note that both sites initially show correlations with temperatures in January and February that are then immediately lost. Correlations of NAO indices with ring width in February are likewise shown to cease at the same time at Ballochbuite and Glen Derry.

Six of the nine chronologies of substrate Scots pine growing on mineral substrate sites, which are clustered on the west coast of northern Scotland, show longer term changes in relationship between climate and ring width before the 1920s. Scots pine for Loch Maree, Shieldaig and Glen Affric show reductions in their positive correlation with January temperature from the 1920s. Scots pine from Beinn Eighe shows a reduction in its positive correlation with February temperature occurring in the 1920s, while correlation in this month ceases at Loch Maree and Glen Affric about the same time. Correlations of NAO indices with ring width in January reduce at Loch Maree and Shieldaig and cease at Beinn Eighe and Glen Affric in the 1920s. Correlations of NAO indices with ring width in February reduce at Loch Maree and Beinn Eighe and cease at Shieldaig and Glen Affric in the 1920s.

Shifts in the correlation between temperature and NAO indices in January and February are similarly evident in the ring widths of two mineral substrate Scots pine chronologies between and to the south of the main Cairngorm and west coast clusters and Glen Affric and Dimmie respectively. At Glen Affric, Scots pine show positive correlations with January and February temperature: these reduce and cease respectively in the 1920s. Positive correlations with January and February NAO indices cease and reduce respectively in 1920s. At Dimmie, Scots pine show positive correlations with January and February temperature respectively; these cease in the 1920s and increase in the 1910s. Positive correlations with February NAO indices increase in the 1910s.

Five chronologies of Scots pine growing on peat substrate are of sufficient length to allow moving correlation functions to extend from at least 1861 and are therefore examined for possible longer term changes in the correlation between climate and ring width. Of the peat substrate sites only one at Eilean Sùbhainn (site B) shows a positive correlation with January temperate and this is found to cease in the 1920s. Scots pine at Eilean Sùbhainn (site A) show a positive correlation with February NAO indices which start in the 1930s. However, a number of other climate variables show changes in correlation with ring width in the 1920s. At Eilean Sùbhainn both sites A and B show positive correlations with October temperature starting in the 1920s. All three Scots pine sites at Abernethy show a positive correlation with NAO indices in May starting in the 1910s.

3.4.4 Pointer year analysis

Table 16 shows the results of pointer year analysis. The period 1880 to 1976 is used for all comparisons.

Table 16: Pointer years affecting Scots pine in the north-west and south-east areas of Northern Scotland for the period 1880 to 1976

Area & substrate	Chronology	Total yrs.	Narrow pointer yrs.	Wide pointer yrs.	**1880**	**1881**	1882	1883	1884	1885	1886	1887	1888	**1889**	1890	1891	1892	**1893**	1894	**1895**	**1896**	1897	**1898**	**1899**	1900	1901	**1902**	1903	**1904**	**1905**	1906	**1907**	**1908**	**1909**	1910	1911	1912	**1913**	**1914**	1915	1916	1917	1918	1919	1920	1921	1922	1923	**1924**	1925	**1926**	**1927**	**1928**	1929	1930	1931	1932	1933	1934	1935	1936	1937	**1938**	1939	**1940**	**1941**	**1942**	**1943**	1944	**1945**	**1946**	1947	**1948**	**1949**	1950	1951	1952	1953	1954	1955	**1956**	1957	1958	1959	1960	**1961**	1962	1963	**1964**	1965	1966	**1967**	1968	**1969**	**1970**	1971	**1972**	1973	**1974**	**1975**	1976
	≥4 sites affected in NW				1	1			1					1				1		1	1		1	1			1		1	1	1	1	1	1				1	1			1	1			1	1	1	1		1	1	1	1						1			1		1	1	1	1		1	1		1	1					1		1				1			1			1		1	1		1		1	1	1
	≥5 sites affected in SE				1	1	1	1		1				1				1		1	1						1		1	1		1	1	1		1		1	1	1			1		1		1				1	1	1	1		1		1		1				1		1	1	1	1	1	1		1	1	1		1		1			1			1		1	1		1	1		1	1	1		1	1		1		1
NW-lowland-bog	ESBE-09	100	27	33	-	+	+		-				-		+			-				-	+		+		-	+			+		-	-		+	+	-	+	-	+		+			+	+	-	-	+	+		-				-	-		+	-		+		-		-	+						+	+			+	-	-	+	+	+		-		-	-		+		+	-	-	+		+	+	-	-	+
NW-lowland-bog	ESDB-12	100	31	28	+	-	+		+				+	-	-		+		-	-	-		+	+		+	-	-			+		-	-	+		+	+	-	-	+				+	+		-	-				-				-			+			+		-	-		+	-				-	+				+	-	-	-	+	+	+		-	-		+			+	-	-	-		+	+	-	-	
NW-lowland-mineral	ESDG-13	100	26	19	-				+					-			+		-	-	-	+	+				+		-	+		+	-			-		+			-	-	+			+				-						-				-	-	+		-	-				+	-		-	+				+		-		+		--			-				+		-	-		+	+	-	-	
NW-lowland-mineral	LCHMAREE	98	35	29	+	-		-	+		-		+	-		-		+	+	-	-	-	+	+			-	-	+	+	+	-		-	+		+	+	+	-			-		-	+	+	-	-		+	+		-		-				+				-	-	-	-	+		-	-			+	+	+			-		-	-		+		-	-		+		-	+	+	-	-		+		-	+	+
NW-foothill-mineral	BNAA-10	100	27	27	+	-		+						-			+	+		-	-		+	+		-	-		+	+	+	-	-	-			+	+				-				+	+	-	-		+	+	-	-		+		+		+		-	+			-	-	+	+	+	-		-	+					-										+	-	-		+	-			+		-	-	+
NW-foothill-mineral	COULIN	98	26	23	+	-			+		-			-	+			+	+	-			+	-			-		+	+		-	-	-	+	+		+	-						-	+							-								+				-	-	+	+	+		-	-	+	-	+	+			-	-		-						-	-		+			+	-	-	-	+	+		-		+
NW-lowland-mineral	ACHA-07	87	24	20	▨	-	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		-		-	-		+	+			-	-	+	+		-			-	+		+			-		-		+		-	-	-	+	+		-			+	-	-	+		+	+	-					-				-	+		-					-		+	+	+			-			-	+		-	-		+			+	
NW-lowland-mineral	SHILEDAIG	98	27	24	+	-			+	+	-	+		-		-		+		-	-		+		-			+						-	-		+	+			-	-	-		+	+		-	+		-	-				+				+		-	-	-	+		+				+				+		-	-		+		-	-		+	+	+		-		-				+	-	+	+
NW-lowland-mineral	PLOCKTON	96	25	31	+	+	-	-	+					-			+		-	-		+	+	+		-		-	+	+	+	-	-	+	+			+	+			-	-			+	+	-	-	-	+	+	-				+					+		-				-	+	-	+	+	+	-				-	+				-	-				+		+	+		-	-		+		-	+	+
NW-foothill-mineral	GLNAFRIC	96	28	18	+	-			+	-				-		+	+			-		+	+		-	-	-		+			+		-		+	-			-	-	-	+	+	-				-		+		-	-						+		-	+		-		-	+			-				+			-					-	-		+		-	-		+			+		-	-				-		
SE-lowland-bog	PITM-M1	100	33	20	+	-		-	-	-		+	+		-	-	-	+	+			-	-	+	+								-	-	-		+		-		+		-	-	+	+		-				-	-	-	+	+	-			+		-	-	-						-	+			-		+	-	-				-		+		-	-				-		+		-		+			-		
SE-foothill-bog	MONM-M1	74	27	21	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	-	-			+	+	-	+	+				-	-		+	-	-	-			+					+	-	-		+		-	-		+				-	+			-	+	+		-	-	-	+	-		+	+	-	-	-	+	+				-	-	-	+	+	-	-	+	+
SE-foothill-bog	ABEB-06	100	33	27	-	-	+			+	-				+		+			+	-			-	+		-		+	-	-			+	+	-	-	-	+		+	+			-	-	-		+	+	-				-		-	-		+		-	-	+	+		-	-	-	+				+	-			-	-			+	+		-	-	+	+	+				-	-	-	+		-	-	+	
SE-foothill-bog	ABEA-16	100	30	19	-	-						-				+	-		+		-	-	+		-	+				+	-	-			+		-	-			+	+		-	-	-		+		-			-		-			+		-	-	+	+		-				+				+	-		-	-	-		-				-		+	+				-	-		+		-	-	+	
SE-foothill-bog	ABEC-21	100	27	20	-	-	+				+	-						+		-	-	+		-						-	-			+	+		-				+	+		-	-				+	+	-	-		-					+		-	-	+		-	-					+		+	-		-			-	-	+	+		-	-			+				-	-		+		-	-	+	
SE-foothill-mineral	ABED-09	98	34	27					+				-	-		+	+			-	-		+	+		-	-	-	+			-				-	+	+		-	+		+	+	-	-	-			+	+	+		-	-			-	-	+	+	-	-	+		-	-	+			+	+	-			-	-	+		-	-	+	+		-	-	+		+		-	-		-		+		-		+	-
SE-foothill-mineral	CFG-13	99	21	23	-	-	+	-			+	-		-	+	+	+			-					+		-				+		-		+	-	-		+	-						-									-			+					+	+	-		-	+						+			-				-		+				-	-		+	+		+		-		+	+		-	+	-
SE-foothill-mineral	CFF-11	99	21	18	+	-		-	+	-	-				+		+	+	-	-		+	+												-		+	+	-	-		+									+										-		-				-	-	-	+	+	+		-		+		-		+	+	-	-			+		-										+		-		-
SE-upland-mineral	CFE-9	99	28	17	+	-	+	-				+				-			+	-	-						-		+	+				-	-			+		-	-						-		-	+	+	+	-									-	-			-	-	-		+	+		-	-	+						+	-			+	-	-	-				+	-	-		+	+		-		
SE-upland-mineral	CFD-11	99	26	21	+	-	+	-		-	-	+	+			+	-			-	-			+			-		+	+	-		+		+	-		+	+	-					-						+	+	-		-		+				-			+	-		-	+							-						-	-				-			+				-	+	+		-		-
SE-upland-mineral	CFA-15	99	24	26	+	-		-				+	-	-				+		-	-			+		+	-		+			-								-		+	+		-						+		-			+	+		-	+			+	+	-	-	-	+	+		-	-		+				+		+	-			+		-				+	+		+	-	-		+	+		-	+	-
SE-upland-mineral	CFB-10	99	30	28	+		+	-	-	-			-	-	+		+			-		+						-		+	+	-	-		+		-		+	+	-			+	+	-	+		-	-			+	+	-		-	+	+		-		-		+	+	-	-		+	+		-	-	-	+					+		-			+		-			+	+			-	-		+	+		-		-
SE-upland-mineral	GLENDERRY	98	25	25	+	-	+		+	-									+	+	-			+		-		-	+	+	+		-	-	-	+	+			+			-	+		-		-			+	+	-	-		+				-						-			+			-			+	-				-	+	-			+		-	-		+			+	-	-	-	+	+			+	
SE-upland-mineral	INVEREY	96	29	26	+		+	-		-	-						-			-		+		-		+	-		+	+		-	-	-	+	+	+		+	-	-	-		+		-	-			+	+	-	-				+	+					-	+	-				+			-	-	+		-				+		-		+	+	-	-		+	+		+	-	-		+	+		-	-	+
SE-upland-mineral	BALLOCHB	98	33	32	+		+	-	-		+		-	-	+	+		+	+	-	-		+	+	-		-	+	+	+		-	-	-			+			-			+			-	-			+	+	-	-		-		+	+	-				+	+	-	-		+		+	-	-	-	+		-		+			-		+	+		-	-	+	+	+	-	+	-	-	-	+	+		-		
SE-foothill-mineral	DIMMIE	96	23	20	+		+	-	-	-									+	+	-	-	-					-		+	+		-	-	-		+		+				-							+				+	-						-					+	+	-		-	+		+		-	-	+		-	-	+		-					+		-			+		-	-	+	+				+

KEY: ☐ = Mineral 🟨 = Peat ▨ = No analysis -/+ = Narrow or wide rings -/+ = Pointer years considered to affect the NW or SE areas (- = Narrow, + = wide), **bold** affect both regions

Between 1880-1976, 15 positive and 16 negative pointer years are established, which affect ≥ 47% of sites where Scots pine grow on mineral substrate in northern Scotland (Table 17). While these 31 pointer years coincide between the NW and SW areas, well over half (37 years) are unique to their particular region. Pointer years analysis further demonstrates the high auto-correlation of Scots pine, observed in the tendency for wide pointer years to be followed by a wide pointer year in the subsequently year (e.g.1904/5, 1913/14 and 1926/7) and conversely narrow pointer years followed by narrow pointer years in the subsequent year (e.g. 1895/6, 1907/8/9, 1940/1/2). There is a noticeable absence of narrow pointer years between 1910 and 1939. Positive and negative pointer years occur conversely in the NW and SW areas in 1918, 1922 and 1976.

Table 17: Pointer years affecting Scots pine growing on mineral substrate over the Highland region of Scotland for the period 1880-1976

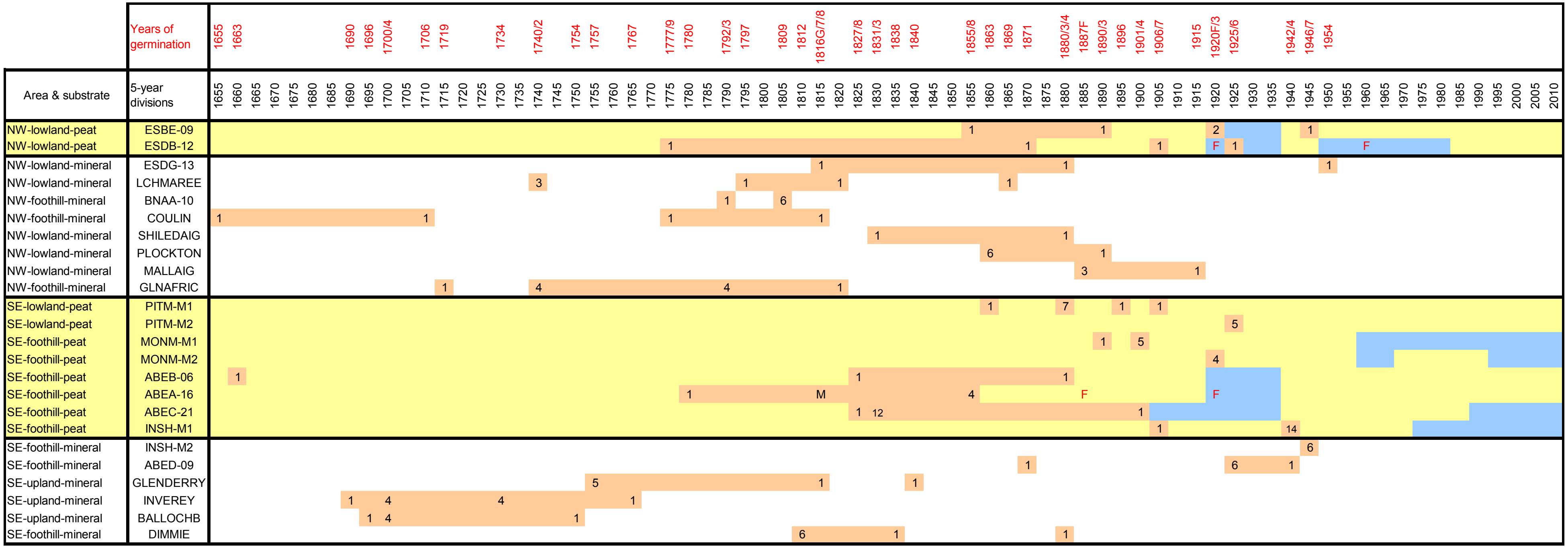
Period	Wide pointer year	Narrow pointer years	Total wide	Total narrow
1880-1889	1880	1881, 1889	1	2
1890-1899	1893	1895, 1996	1	2
1900-1909	1904, 1905	1902, 1907, 1908, 1909	2	4
1910-1819	1913, 1914		2	0
1920-1929	1926, 1927	1928	2	1
1930-1939	1938		1	0
1940-1949	1943, 1949	1940, 1941, 1942, 1948	2	4
1950-1959		1956	0	1
1960-1969	1964, 1967	1969	2	1
1970-1979	1972, 1975	1974	2	1
		Total	**15**	**16**

The pointer years identified in the Scots pine growing on peat were compared to those identified from pine growing on mineral substrates in the NW and SE areas. The two chronologies from Eilann Sùbhainn matched closest with the pointer years from the NW area, with 41% and 65% of pointer years in the chronologies from site A and B matching respectively. Pointer years identified in three chronologies from Abernathy match well together, however most occur in different years to those identified from mineral growing pine from the SE area, with only 32% of the years matching. Pointer years in the chronologies from Pitmaduthy Moss A and Monadh Mor A, similarly show poor matching, less than 27% of the years of either area coincide.

3.4.5 Common phases of germination and growth reduction

Table 18 shows a summary of germination and growth reduction identified from modern Scots pine sites in northern Scotland; no clear common periods of germination are identified. Between 1920 and 1940 pine at Abernethy and Eilann Sùbhainn show a general reduction in radial growth. It is not possible to establish whether this decline is related to possible fires at this time, or a common climatic response of the pine growing on these peat substrate sites. The absence of germinations on mineral sites from 1920 and on peat substrate sites from the mid 1950s is an artefact of the general selection of older trees for dendrochronological analysis. With few exceptions, after an initial main phase, pine germination continues for an extended period of between 30 to 80 years.

Table 18: Summary diagram of recruitment phases of Scots pine in northern Scotland



	Years of germination	1655	1663						1690	1696	1700/4		1706	1719			1734		1740/2		1754	1757		1767		1777/9	1780		1792/3	1797		1809	1812	1816G7/8		1827/8	1831/3	1838	1840			1855/8	1863	1869	1871		1880/3/4	1887F	1890/3	1896	1901/4	1906/7		1915	1920F/3	1925/6			1942/4	1946/7	1954												
Area & substrate	5-year divisions	1655	1660	1665	1670	1675	1680	1685	1690	1695	1700	1705	1710	1715	1720	1725	1730	1735	1740	1745	1750	1755	1760	1765	1770	1775	1780	1785	1790	1795	1800	1805	1810	1815	1820	1825	1830	1835	1840	1845	1850	1855	1860	1865	1870	1875	1880	1885	1890	1895	1900	1905	1910	1915	1920	1925	1930	1935	1940	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010
NW-lowland-peat	ESBE-09																																									1							1					2					1													
NW-lowland-peat	ESDB-12																									1																			1							1			F	1							F										
NW-lowland-mineral	ESDG-13																																	1													1														1												
NW-lowland-mineral	LCHMAREE																		3											1					1									1																													
NW-foothill-mineral	BNAA-10																												1			6																																									
NW-foothill-mineral	COULIN	1											1													1								1																																							
NW-lowland-mineral	SHILEDAIG																																				1										1																										
NW-lowland-mineral	PLOCKTON																																										6						1																								
NW-lowland-mineral	MALLAIG																																															3						1																			
NW-foothill-mineral	GLNAFRIC													1					4										4						1																																						
SE-lowland-peat	PITM-M1																																										1				7			1		1																					
SE-lowland-peat	PITM-M2																																																							5																	
SE-foothill-peat	MONM-M1																																																1		5																						
SE-foothill-peat	MONM-M2																																																						4																		
SE-foothill-peat	ABEB-06		1																																	1											1																										
SE-foothill-peat	ABEA-16																										1							M								4						F							F																		
SE-foothill-peat	ABEC-21																																			1	12														1																						
SE-foothill-peat	INSH-M1																																																			1							14														
SE-foothill-mineral	INSH-M2																																																											6													
SE-foothill-mineral	ABED-09																																												1											6			1														
SE-upland-mineral	GLENDERRY																					5												1					1																																		
SE-upland-mineral	INVEREY								1		4						4							1																																																	
SE-upland-mineral	BALLOCHB									1	4										1																																																		
SE-foothill-mineral	DIMMIE																																6					1									1																										

KEY: ☐ = Mineral 🟨 = Peat 🟧 = Period of germination 🟦 = Decrease radial growth, M = Mammal, F = Fire, 1 = Number of trees germinated. Note: Plantations sites not shown

3.4.6 Simple linear correlation of climate data and ring width

Additional analysis was undertaken to help highlight the interrelationships between climate data, tree-rings, and site variables and a number of variables were compared (Table 19). Climate data was used from LOCCLIM (Grieser 2005)

Table 19: Climate data and tree–ring variables used for simple correlation.

	Latitude (dec. deg.)	Longitude (dec. deg.)	Altitude (m)	Mean Jan temp (°C)	Mean July temp (°C)	Total annual precipitation (mm)	Mean Jan wind speed (m/s)	Raw data - mean ring width (mm)	Standardised chronology - mean sensitivity	Standardised chronology - serial autocorrelation	Standardised chronology - mean correlation
Chronology Name	**Lat**	**Long**	**Alt**	**Jan°C**	**July°C**	**Rainfall**	**Wind**	**Raw-MR**	**Std-MS**	**Std-R1**	**Std-Rbar**
BODG-09	58.45	-4.30	200	1.6	14.5	1255	6.6	2.82	0.18	0.25	0.44
STWB-13	58.35	-4.24	25	3.6	13.2	887	7.1	2.31	0.20	0.64	0.50
ESBE-09	57.69	-5.49	50	2.8	13.9	1433	7.3	0.87	0.21	0.12	0.31
ESDB-12	57.69	-5.49	50	2.8	13.9	1433	7.3	0.86	0.19	0.44	0.37
ESDG-13	57.69	-5.49	50	2.8	13.9	1433	7.3	1.19	0.19	0.11	0.37
LCHMAREE	57.65	-5.42	100	2.2	14.5	1606	6.9	1.47	0.14	0.31	0.32
BNAA-10	57.62	-5.36	300	-0.1	16.4	2341	5.4	1.10	0.16	0.05	0.26
COULIN	57.55	-5.35	250	0.2	16.1	2201	5.7	1.06	0.12	0.29	0.32
ACHA-07	57.61	-4.94	130	1.3	15.1	1538	6.2	1.79	0.18	0.35	0.38
SHIELDDAG	57.52	-5.62	12	3.1	13.7	1435	7.6	1.92	0.12	0.47	0.34
PLOCKTON	57.35	-5.63	100	1.9	14.7	1804	7.0	2.23	0.12	0.38	0.39
MALLAIG	57.00	-5.84	100	2.2	14.7	1857	7.0	3.38	0.12	0.69	0.34
GLNAFRIC	57.30	-5.00	300	-1.1	16.5	2294	5.1	1.12	0.12	0.21	0.30
PITM-M2	57.77	-4.07	100	1.4	15.1	1117	5.9	2.41	0.19	0.24	0.38
PITM-M1	57.77	-4.07	100	1.4	15.1	1117	5.9	0.79	0.19	0.63	0.35
MONM-M1	57.55	-4.36	200	0.1	16.0	1556	5.7	1.59	0.16	0.49	0.38
ABEA-16	57.24	-3.68	220	-1	16.3	1496	4.8	0.61	0.17	0.27	0.29
ABEB-06	57.24	-3.68	220	-1	16.3	1496	4.8	0.76	0.21	0.31	0.35
ABEC-21	57.24	-3.68	220	-1	16.3	1496	4.8	0.64	0.18	0.40	0.32
CFG-13	57.28	-3.83	270	-1.7	16.7	1722	4.4	1.44	0.13	0.20	0.38
ABED-09	57.24	-3.68	220	-1	16.3	1496	4.8	1.78	0.17	0.12	0.24
CFF-11	57.13	-3.84	280	-1.6	16.5	1638	4.5	1.59	0.13	0.25	0.24
CFE-11	57.13	-3.84	400	-2.8	16.8	1976	3.6	0.72	0.15	0.18	0.34
CFD-11	57.13	-3.84	450	-3.2	16.9	2117	3.2	0.49	0.16	0.17	0.51
CFA-15	57.13	-3.84	500	-3.7	17.1	2258	2.9	1.09	0.13	0.15	0.46
CFB-10	57.13	-3.84	550	-4.1	17.2	2400	2.5	1.03	0.15	0.33	0.44
GLNDERRY	57.07	-3.59	400	-2.2	16.3	2099	3.6	1.28	0.13	0.09	0.42
INVEREY	57.02	-3.58	500	-3.0	16.4	2436	2.9	1.14	0.12	0.25	0.37
BALLOCHB	56.95	-3.32	381	-1.0	15.7	1815	3.6	1.32	0.13	0.26	0.36
DIMMIE	56.13	-3.33	200	1.4	15.0	974	4.7	1.73	0.15	0.47	0.38

Simple linear correlation coefficients (*r*-values) were calculated between chronology data (sixteen chronologies with an expressed population signal (EPS) ≥ 0.85 and the fourteen chronologies with a range of ESP from 0.70-0.84) and climate (Table 20). This identified positive relationships of ring width, January temperature ($r = 0.48$) and wind ($r = 0.46$), and a negative relationship with July temperature ($r = -0.47$). Ring width was also found to be negatively related with altitude ($r = -0.40$) and mean ring width sensitivity strongly correlated ($r \geq -0.63$) with rainfall. The strong influence of prior growth on ring width is shown in the correlations of auto-correlation (R1) with all the climate variables. However, considerable care is required in interpreting the statistical significance of large sets of correlation. If a statistical significance level of $p < 0.0.5$ is accepted, the 5% (or 1 in 20) of the values identified as significant are likely to be spurious.

Table 20: Correlation matrix of climate data and tree–ring variables

	Lat	*Long*	*Alt*	*Jan°C*	*July°C*	*Rainfall*	*Wind*	*Raw-MR*	*Std-MS*	*Std-R1*	*Std-Rbar*
Lat	1.00										
Long	-0.41	1.00									
Alt	-0.50 *	0.60 ***	1.00								
Jan°C	0.52 *	-0.66 ***	-0.95 ***	1.00							
July°C	-0.51 *	0.58 ***	0.86 ***	-0.95 ***	1.00						
Rain	-0.34	-0.02	0.76 ***	-0.69 ***	0.67 ***	1.00					
Wind	0.60 ***	-0.78 ***	-0.95 ***	0.96 ***	-0.88 ***	-0.58 ***	1.00				
Raw-MR	0.23	-0.28	-0.40 *	0.48 *	-0.47 *	-0.32	0.46 *	1.00			
Std-MS	0.48 *	0.04	-0.44	0.37	-0.36	-0.63 ***	0.34	-0.14	1.00		
Std-R1	0.09	-0.16	-0.46 *	0.47 *	-0.45 *	-0.46 *	0.40 *	0.40 *	0.07	1.00	
Std-Rbar	0.15	0.20	0.21	-0.09	-0.10	-0.02	-0.16	0.12	0.08	0.17	1.00

* *P* <0.05, *** *P* <0.001

3.4.7 Comparisons between 1881-1930 and 1931-1980

Cross-matching, correlation analysis with climate and pointer years all indicate different responses between the NW and SE area populations of Scots pine. To try to amplify the differences, four mean area chronologies were established. The NW mineral substrate chronologies: ESDG-13, LCHMAREE, BNAA-10, COLIN, ACHA-7, SHIELDAG and PLOCKTON were used to form a mean chronology called OCEAN-PN. The chronology MALLAIG was not included due to its lack of cross-matching. The NW peat substrate chronologies: ESBE-9 and ESDB-12 were used to create a mean chronology called OCEAN-BP. The SE mineral substrate chronologies: CFG-13, CFF-11, CFE-9, CFD-11, CFA-15, CFB-10, CFC-3, GLENDERRY, INVEREY and BALLOCHB were used to create a mean chronology called BORAL-PN. The SE peat substrate chronologies: ABEA-16, ABEB-6 and ABEC-21 were used to create a mean chronology called BORAL-BP.

The mean regional chronologies BORAL-PN and OCEAN-PN, together with a sequence established from pointer years called POINT-YR were correlated against January, February, July and August temperatures, August rainfall and February NAO indices, for two time periods 1881-1930 and 1931-1980 (see Appendix XI). These months had already been identified as significant to pine growth through moving correlation functions. Comparing the mean values, the two periods show a 0.8 (84%) decrease in February NAO Index, which is accompanied by decreases in the Scottish Mainland temperature (SMT) data of 0.3°C and 0.2°C in January and February, a 17% reduction in August rainfall at Braemar, and 12% and 33% reductions of mean ring width in the BORAL-PN and OCEAN-PN chronologies again respectively. For the period 1881-1930, the BORAL-PN chronology shows significant positive correlation with temperature in January, February, July and August, against both the Scottish Island temperature (SIT) and Scottish Mainland temperature (SMT) data sets. The sequence POINT-YR (pointer years) is positive correlated with February, July and August temperature. Correlations are slightly more significant against the SIT data. For the period 1931-1980 the OCEAN-PN chronology shows significant positive correlation with temperature in February, July and August. The OCEAN-PN chronology sequence shows positive correlation with NOA in February. The BORAL-PN chronology only shows positive correlation against temperature in February from the SMT data. The sequence POINT-YR is positively correlated with temperature in January and February. Significant correlations are all slightly high against the SMT data.

The results show that the climate has altered considerably from 1881-1930 to 1931-1980. In the earlier period the correlation with pointer years indicate temperature in February, July and August are significant for Scots pine ring growth across northern Scotland. The BORAL-PN chronology is most significantly positively correlated with temperature in July and August, but positive correlations with temperature in January and February are only slightly less. The OCEAN-PN chronology shows no significant correlation to individual months over this period. In the latter period, correlation with pointer years identifies that temperature in January and February becomes the most important determinate for Scots pine ring growth in northern Scotland and the earlier periods correlation with temperature July and August are lost. The OCEAN-PN chronology becomes significantly positively correlated with temperature in February, July and August against both the SIT and SMT data and with temperature in January, but only against the SMT data. The OCEAN-PN chronology also develops significant negative correlation with the Braemar rainfall for August. This correlation is unexpected because it is the component site chronologies of BORAL-PN that show correlation with this month in the moving response analysis. The OCEAN-PN chronology also develops a positive relationship with NAO indices in February. The peat pine chronologies have few component chronologies and so are likely to contain site specific influences, therefore their statistical correlations are less reliable.

4 DISCUSSION

The number and range of chronologies in this research (9 peat substrate and 26 mineral substrate sites), compared using common methodologies, make this the largest dendroclimatological investigation on the growth of modern Scots pine in northern Scotland and the first to examine pine growing on peat. The cross-matching of subfossil Scots pine from 9 sites has produced the first Neolithic regional tree-ring chronology for Scotland, enabling an unprecedented investigation of the growth of pine during this period.

Briffa and Cook (1990) caution that attempts to compare the results of response function analysis of different chronologies are fraught with problems and that it is prudent to use a common methodology to best enable comparison and to interpret only the gross features of individual analysis. This caution is considered well applied to all analysis between tree-ring growth and climate. In order to identify broad patterns in the growth characteristics of Scots pine and its relationship with site factors and climate, developing a number of chronologies (both from the past and present) has been focused on, in favour of depth of chronology replication. As a result, a desirable expressed population signal (EPS) level of ≥0.85 was not achieved in 7 of the modern pine chronologies developed. While earlier studies suggested 12 trees are typically sufficient to develop chronologies with a sufficient EPS level, this analysis suggests that a minimum of 20 trees should normally be considered, particularly in the NE area.

To help understand the growth characteristics and relationships between climate and Scots pine growing on peat in the past, it is desirable to clarify the present-day relationships of Scots pine growing on mineral and peat substrates. This chapter is therefore structured under three main headings: Caledonian Pine Forest (section 4.1), Modern Bog Pine (section 4.2) and Holocene Bog pine (section 4.3). The possible implications of Scots pine as a proxy for the direction of prevailing wind are then discussed under the proposed name for this new discipline heading: Dendroaeology (section 4.4). This final section also examines some of the implications for climate change and the response of pine to it.

4.1 Caledonian Pine Forest

The main aim of this section is to extend the current understanding of the relationship between modern Scots pine growth in Scotland and climate. Direct comparisons of all available mineral substrate pine chronologies in Scotland are made possible by the chronologies having undergone common methods of dendroclimatological analysis. The influence of North Atlantic Oscillation on the radial growth of Scots pine in Scotland is also examined for the first time.

4.1.1 Relationships of tree-ring growth with monthly climate variables

Schweingruber (1979) states that the cambial activity and growth rate of cell walls in the latewood of all conifer species from cool-humid regions are limited mainly by summer temperature. Early studies on Northern European Scots pine have usually reinforced the importance of the relationship between radial growth and summer temperature (Hughes *et al.* 1984, Briffa *et al.* 1988, Luckman *et al.* 1997). However, these authors were mainly concerned with the reconstruction of past climates. To improve correlations they used not only ring widths but also the maximum density of the latewood. This second variable, being a strong function of summer temperature (Schweingruber *et al.* 1979), greatly improves the ability to predict summer temperature.

In agreement with Schweingruber *et al.* (1979), correlation and moving correlation functions find a positive relationship between summer (July-August) temperature and ring width. This is consistent with the radial growth of Scots pine being limited at high altitude sites in northern Scotland. The relationship is particularly evident at sites ≥300 m in the SE area (Figure 81 and Table 20), but less so in the NE, probably due to the low altitude of most of these sites.

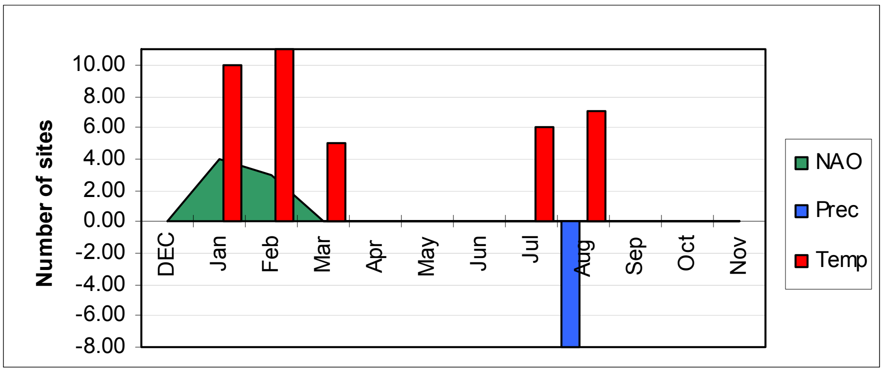


Figure 81: Number of mineral substrate Scots pine sites out of 11 in the SE area of northern Scotland for which correlation functions show significant relationships with monthly climate data between 1881 and 1960.
+ve/-ve = Sites showing a positive or negative correlation respectively, but only showing those with totals ≥ 3 for clarity.

Earlywood production in Scots pine has been considered principally controlled by prior growth and microsite conditions (Schweingruber *et al.* 1979) and therefore to have no direct relationship to climate. However, the results of this research show January and February temperatures to be at least as important, and often more important, than summer (July-August) temperatures in the radial growth of Scots pine. This relationship is significant throughout the SE and at five sites in the NW. The relationship was first shown in Scotland by Hughes (1987) and later confirmed by Grace and Norton (1990). While rarely discussed, significant positive correlations between winter temperature and radial growth of Scots pine have also been identified from studies in Europe (Table 21):

- Lake Ann Basin – Sweden – in February and March (Linderholm *et al.* 2003)
- Kevo, N. Finland – in January and February (McCarroll *et al.* 2003).
- Lycksele – Sweden – in January, February and March (Linderholm *et al.* 2002)
- Gullhult – Sweden – in February and March (Linderholm *et al.* 2002)
- Berlin, Germany – in February, but also January and March (Lührte von 1991).
- Mountain of Prades, Spain - mainly in December (Gutiérrez 1989)

A study in Siberia also found Scots pine at higher latitudes to have adapted to maximally exploit the earliest available heat sum; and conditions of the second half of the growing season were found to have less effect on radial growth (Savva *et al.* 2001). The significance of this relationship between January and February temperature on the radial growth of pine has previously been largely overlooked in dendroclimatological research.

Fixed period and moving correlation functions identify Hurrell's (1995) NAO indices (a proxy measure for wind in some areas) to have significant influence on the growth of Scots pine in northern Scotland during winter (mainly in January and February). This positive relationship is shown at four sites in the NW (Loch Maree, Beinn Eighe, Shieldaig, Glen Affric) and three sites in the SE (Abernethy, Inverey and Dimmie). Significant correlations between Scots pine growth and NAO indices have previously been shown in a Fennoscandia study (Table 21):

Table 21: Correlation analysis of Scots pine tree-ring data with monthly climatic variables in Europe.

			Temperature (Mean)												Precipitation												North Atlantic Oscillation (Harrell 1995)											
Soil	Brief Description of location & short reference	Selected Interval (years)	DEC-T	Jan-T	Feb-T	Mar-T	Apr-T	May-T	Jun-T	Jul-T	Aug-T	Sep-T	Oct-T	Nov-T	DEC-P	Jan-P	Feb-P	Mar-P	Apr-P	May-P	Jun-P	Jul-P	Aug-P	Sep-P	Oct-P	Nov-P	DEC-O	Jan-O	Feb-O	Mar-O	Apr-O	May-O	Jun-O	Jul-O	Aug-O	Sep-O	Oct-O	Nov-O
Dry	K130 - Tyrol - Austria (Oberhuber 1998)	1921-1990 (70y)																+	+	+																		
Dry	K131 - Tyrol - Austria (Oberhuber 1998)	1921-1990 (70y)																	+		+																	
Dry	K132 - Tyrol - Austria (Oberhuber 1998)	1921-1990 (70y)					-												+	+	+																	
Dry	K134 - Tyrol - Austria (Oberhuber 1998)	1921-1990 (70y)					-												+	+																		
Dry	K135 - Tyrol - Austria (Oberhuber 1998)	1921-1990 (70y)					-												+																			
Dry	K136 - Tyrol - Austria (Oberhuber 1998)	1921-1990 (70y)																	+	+	+																	
Dry	K137 - Tyrol - Austria (Oberhuber 1998)	1921-1990 (70y)																	+		+																	
Dry	K138 - Tyrol - Austria (Oberhuber 1998)	1921-1990 (70y)					-												+	+																		
Dry	K101 - Nr. Innsbruck - Austria (Oberhumber 2002)	1907-1993 (87y)						-		+											+																	
Dry	K115 - Nr. Pfunds - Austria (Oberhumber 2002)	1902-1993 (92y)																		+	+	+																
Dry	K139 - Nr. Otz - Austria (Oberhumber 2002)	1912-1997 (86y)																		+	+	+																
Dry	N1 - Norway (Linderholm 2003)	1901-1990 (90y)							0.20										0.20		-0.22							-0.22				-0.18		-0.30	0.28			
Dry	N2 - Norway (Linderholm 2003)	1901-1990 (90y)							0.19		0.21									0.20	-0.18		0.23				0.20	-0.22						-0.28	0.10			
Dry	N3 - Norway (Linderholm 2003)	1901-1990 (90y)				0.19		0.20	0.44	0.19											-0.22							-0.18	-0.12		0.12	-0.16		-0.20	0.18			
Dry	S1 - Sweden (Linderholm 2003)	1901-1990 (90y)	0.22						0.16	0.44	0.18						0.20			0.20		-0.20										0.14	0.20					
Dry	N4 - Norway (Linderholm 2003)	1901-1990 (90y)	0.22		-0.18	0.20				0.32										0.20		0.17											0.10	-0.12				
Dry	S2 - Sweden (Linderholm 2003)	1901-1990 (90y)				0.16			0.20	0.35					-0.18												0.30			-0.10		0.20			0.12			
Dry	S3 - Sweden (Linderholm 2003)	1901-1990 (90y)		-0.14					0.14												0.20	0.12						0.22		-0.12					0.12			
Dry	F1 - Finland (Linderholm 2003)	1901-1990 (90y)	0.24		0.18	0.21	0.20		-0.30							-0.20		0.20		0.10	0.22	0.23					0.20	0.30	0.12	0.28			-0.16					
Dry	F2 - Finland (Linderholm 2003)	1901-1990 (90y)				0.10	-0.21			0.20											0.22	0.12	0.10				0.10					0.15	0.12		-0.12			
Dry	110 m - Kevo - N. Finland (McCarroll 2003)	1961-1990 (29y)		+	+																																	
Dry	155 m - Kaamanen - N. Finland (McCarroll 2003)	1961-1990 (29y)		+																																		
Dry	220 m - Laanila - N. Finland (McCarroll 2003)	1961-1990 (29y)				+			+	+	+																											
Dry	Komi - E. European Russia (Drobyshev 2004)	1897-1992 (96y)								0.20																												
Dry	North Karelia - Finland (Miina 2000)	?																		0.30																		
Dry	1100 m - NTOPS - Parades - N. Spain (Gutierrez, 1989)	1955-1982 (27y)	0.20						-0.10	-0.11								0.18			0.16																	
Dry	880 m - NTBPS - Parades - N. Spain (Gutierrez, 1989)	1955-1982 (27y)	0.22						-0.10									0.18			0.16																	
Dry	530 m - Lake Ann Basin - Sweden (Linderholm 2001)	1911-1979 (68y)		-0.09	0.10	0.18	0.16													0.15	0.20	0.24	0.16															
Bog	528 m - Lake Ann Basin - Sweden (Linderholm 2001)	1911-1979 (68y)													0.05					0.16	0.20	0.11	0.08															
Bog	Estonia (Laanelaid 1982)	?						-														-																
Bog	N. Sweden (Lundh 1925)	?											?	?											?	?												
Bog	Central Russia (Vaganov and Kachaev 1992)	?											?	?											?	?												
Bog	Angerusjarvi - Sweden (Linderholm 2002)	1891-1990 (100y)		+			+	+	+						-						-			+														
Bog	Stortjaderberget - Sweden (Linderholm 2002)	1891-1990 (100y)							+						-	-	-						-															
Bog	Arson - Sweden (Linderholm 2002)	1891-1990 (100y)	+					+		+	+	+				-	-																					
Bog	Bredmosseni - Sweden (Linderholm 2002)	1891-1990 (100y)					+	+				-			-	-	-			-			-															
Bog	Anebymossen - Sweden (Linderholm 2002)	1891-1990 (100y)	+			+			+		+					+				+	+		+															
Bog	Hanvedsmossen - Sweden (Linderholm 2002)	1891-1990 (100y)			+	+				+							+			+	+	-																
Bog	Hanvedsmossen - Sweden (Linderholm 1999)	1901-1940 (40y)								0.30	0.30					0.34																						
Drained Bog	Hanvedsmossen - Sweden (Linderholm 1999)	1901-1940 (40y)				0.38	0.50					-0.32			0.30	0.45			-0.38																			
Dry	Hanvedsmossen - Sweden (Linderholm 1999)	1901-1940 (40y)	0.44																	0.45		0.34																
Dry	Stockholm - Sweden (Linderholm 2002)	1891-1990 (100y)				+				-										+	+																	
Dry	Norberg - Sweden (Linderholm 2002)	1891-1990 (100y)				+	+	-	-		-					-		-		+	+	+																
Dry	Gullhult - Sweden (Linderholm 2002)	1891-1990 (100y)			+	+	+	+	-			-						-					+															
Dry	Ann - Sweden (Linderholm 2002)	1891-1990 (100y)	+					+	+	+	+	+						+			-		+	+														
Dry	Lycksele - Sweden (Linderholm 2002)	1891-1990 (100y)		+	+	+			+	+						-					-																	
Dry	Tornetrask - Sweden (Linderholm 2002)	1891-1990 (100y)					+		+	+																												

KEY = + = positive, - = negative relationship ☐ = Mineral 🟨 = Peat ▨ = no analysis ? = span of analysis not known

- In Finland – two sites show a positive response in January and one site in February (Linderholm *et al.* 2003)
- In Norway – three sites show a negative response in January and one site in February (Linderholm *et al.* 2003)

As expected at low altitude sites in the NW area (and also at lower latitude in the case of Dimmie located much further south near Edinburgh), summer temperature is shown not to be a significant limiting factor on the growth of Scots pine, whereas both winter temperature and NAO, particularly in January and February, are. So it needs explaining why the growth of Scots pine is found to be strongly related to winter temperature and NAO indices.

4.1.2 Physiological relationships with winter weather

While Scots pine is extremely cold hardy in its winter condition, it can show yellowing and browning of its needles in winter and/or early spring (Sakai and Larcher 1987). Grace and Norton (1990) identify conspicuous winter browning in Scots pine at the tree line in the Cairngorms, which is absent at lower altitudes. Short/cold growing season leading to insufficient development of the leaf cuticle had been suggested to lead to desiccation during winter and spring when soil is frozen (Tranquillini 1979). In general, however, it has now been identified that cuticular development is not usually impaired, although the leaf surface can become abraded by wind and wind-borne particles (Grace and Norton 1990). Gales are especially common in January and February, when the soil is often frozen, but even then the store of water retained in the tree is thought likely to be sufficient to sustain cuticular transpiration over long periods (Grace *et al.* 2002). Nevertheless, disruption of the epidermis and large scale loss of needles in winter is likely to reduce the radial growth increment the following summer, because old needles make a significant contribution to total photosynthesis (Linder and Troeng 1980).

A second winter physiological mechanism which could be a function of ring width is suggested by conifers increasing weight whilst they remain dormant in mild winters (Bradbury and Malcolm 1978). Conifers gain weight because they accumulate carbohydrates. This is due to the rate at which glucose can be used in biosynthetic processes, which is generally more restricted by low temperature than is the rate of net photosynthesis. Food reserves accumulated in winter may then be used in the early wood formation of a new tree-ring. Drobyshev *et al.* (2004) identified a positive impact of previous year temperature on earlywood growth and suggests that the formation of earlywood is controlled by the amount of carbohydrate reserves built-up during the previous season. Photosynthetic capacity is reduced following exposure to low temperature. So that winter anticyclonic conditions with bright sunshine are unlikely to contribute much to winter photosynthetic production (Öquist 1983). However, the oceanic conditions of Scotland may allow Scots pine to take advantage of mild winter temperatures, which allow thawing and thus enhance the availability of water. So that winter photosynthesis becomes a significant positive factor in radial growth.

The positive correlation of ring width with January and February temperature found in this research shows winter conditions have a significant role in the growth of Scots pine in Scotland near its altitudinal margins. Mild winters (in terms of temperature) due to Scotland's close proximity to the Atlantic Ocean may allow winter photosynthesis to become a significant positive factor in radial growth. However, more NW sites show positive correlations of ring width with NAO Indices in January and February (Table 14). This suggests wind could be the most significant limiting factor on Scots pine growth at its western margin. Harsh winter gales may lead to loss and damage to needles/branches/tree, thereby reducing a tree's photosynthetic potential and so its radial growth increment the following summer. This provides empirical evidence supporting Carlisle and Brown's (1968) observations that the altitudinal limit of Scots pine is probably determined by a combination of temperature and exposure to wind blast, although it should be recognised that both monthly temperature and wind are closely correlated (Table 20).

4.1.3 Differences between the NW and SE mineral substrate populations

With few exceptions, Scots pines that grow on mineral substrate sites in north Scotland have formative growth rates ≥ 1.5 mm yr^{-1} (Figure 76). Pine growing at mineral substrate sites in the NW area (i.e. those under 100 m and with the warmest winter temperatures) have the highest formative radial growth rate range (2.17-3.83 mm yr^{-1}); those over 120 m have the lowest (1.03-1.68 mm yr^{-1}). In comparison, Scots pine in the more continental climate SE area (which are all over 270 m) have a formative radial growth rate range of 1.75-2.22 mm yr^{-1}. The disparity of high and low formative radial growth rates between the higher and lower altitude sites respectively in the NW area, suggests the importance of altitude and probably exposure in the growth of Scots pine in Scotland. The precise natures of these relationships are further examined.

There are considerable differences between the climatic relationships of Scots pine growing on mineral substrate in the NW and SE areas of Northern Scotland. Correlation function analysis on 11 Scots pine chronologies in the SE area of northern Scotland indicate that winter temperature (in January and February) as well as summer temperature (in July and August) are the most important determinants of the ring width, these correlations are positive (Figure 81). Ring width is also negative correlated with rainfall in August at eight sites. Scots pine growing at sites between 400 and 500 m altitude show the most significant relationships with these climate factors.

In contrast, Scots pine growing at 9 sites in the NW area show far fewer common relationships to monthly temperature, rainfall and NAO indices. The most common significant relationship is a positive one with NAO indices in January, February and April which is evident at four sites (Figure 82).

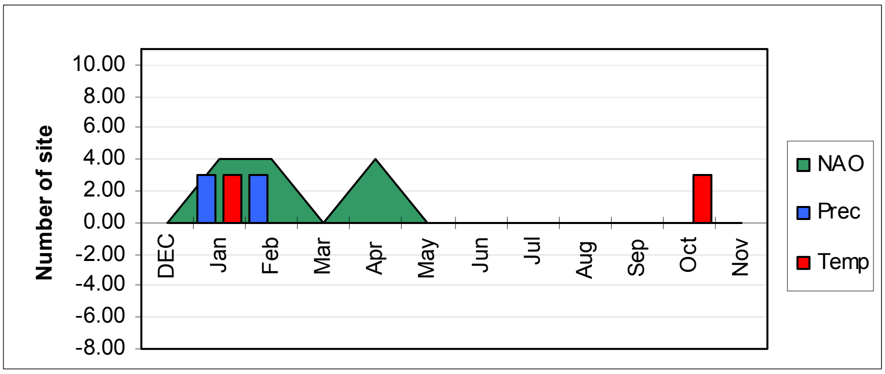


Figure 82: Number of mineral substrate Scots pine sites out of 9 in the NW area of northern Scotland for which correlation functions show have a significant relationship with monthly climate data between 1881 and 1960.
+ve/-ve = Sites showing a positive or negative correlation respectively, but only showing those with totals ≥ 3 for clarity.

Three sites show positive relationships with temperature and rainfall in January and rainfall in February. Scots pine growth at three sites show a positive relationship with temperature in October. Scots pine growing in the NW area rarely show the response with monthly temperature in summer (July or August) seen in the SE area chronologies, but two exceptions occur at higher altitude sites. The most consistent relationship on pine radial growth is a positive one with NAO indices in winter (January, February and April), however this climatic factor is known to vary in intensity at different periods of time.

The relationships found in this research between ring width and both monthly temperature and rainfall in the SE area are in good agreement with earlier studies in Scotland (Hughes *et al.* 1984, Grace and Norton 1990) and help validate the climate analysis methods used in this study. Grace and Norton (1990) identified higher altitude sites (>300m) tended to show an increase in the correlations between Scots pine chronologies. This pattern is clearly evident in the high cross-matches between chronologies in the SE area. Unfortunately, the absence of sites above 300m in the NW area prevents direct comparison. The two chronologies from the highest sites analysised in the NW area (Beinn Eighe at 300 m and Coulin at 250 m) only show common monthly response with NAO indices in April. The expressed population signal values for the chronologies help confirm that a common climate signal is stronger in the Scots pine from sites in the SE area (Table 13). This evidence is consistent with the tree growth in the SE area becoming increasingly controlled by climate nearer its environmental limits, whereas in the NW area precipitation and temperature are less limiting to tree growth. NAO indices indicate wind has a more significant relationship to pine growth in the NW area.

4.1.4 Boreal or Oceanic Forest?

Where tree-ring series from trees within a “well-defined” ecological area cross-match, they can be considered as records of the same climatic parameters. This analysis finds consistent differences between the cross-matching, formative growth rates, moving correlation functions and pointer years, of Scots pine growing in the NW and SE areas of northern Scotland. This evidence suggests the possibility of two separate populations.

A simple distinction between the Scots pine chronologies of the NW and the SW areas of northern Scotland are that the former fall within Hyperoceanic and Euoceanic bioclimatic sub-sectors (Birse 1971), while the latter are Hemioceanic. In Norway, pinewoods along the west coast districts located within a climatic boundary with annual precipitation above 1200 mm and average air temperature in February above 0°C are classified as oceanic pine forest types, while pinewoods located further inland are classified as boreal pine forest types (Øyen, 1998). Western Scotland receives between 2000-2800 mm and eastern Scotland 900-1300 mm of precipitation yearly, the mean winter temperate for northern Scotland is 0.02°C, suggesting that the Norway criteria could be applicable for forest type to northern Scotland. No site of Scots pine included in the OCEAN-PN chronology has a mean February temperature under 1°C, and the sites included in the BORAL-PN chronology have mean temperature in this month below -0.4°C (with the slight exception of Abernathy which has a mean of 0.1°C). Additionally, there is some genetic evidence (section 1.1.6) to suggest that the Caledonian Pine forest might be considered in terms of two populations (Oceanic and Boreal) corresponding to the oceanic climatic areas of western Scotland and more continental areas of eastern Scotland. If substantiated, such a division would have important implications for the future management of the Caledonian Pine Forest and particularly in consideration of climate change. One limitation of this research is the lack of high altitude sites of the NW area for comparisons between the SE and NW areas. The sampling of higher altitude pine sites in the NW area is recommended to help clarify possible differences between the two populations.

4.1.5 Atypical sites

The chronologies developed from mineral substrate pine growing at Beinn Eighe and Eilann Sùbhainn display formative growth rates comparable with other mineral substrate sites in this research (i.e. > 1 mm yr^{-1}). Both sites however show subsequent reductions in radial growth shortly after entering maturity comparing to bog pine (i.e. < 1 mm yr^{-1}, see Figure 76). Some trees at Beinn Eighe were noted during their sampling to have originated from waterlogged conditions and those from Eilann Sùbhainn are located on the shore of the loch. The reduction of radial growth at both sites to levels comparable with pine growing on bog (further discussed in section 4.2.1) together with the apparent susceptibility of these sites to changes in water level suggest the cause could be an increase in waterlogging.

Further examination of the chronology developed from Scots pine growing on mineral substrate on the loch edge at Eilann Sùbhainn shows sudden growth reduction from 1.71 mm yr^{-1} in the 1900s to 0.30 mm yr^{-1} in the 1930s, the growth rate reduces to a level comparable with that recorded for pine growing on bogs. The individual plots of ring width (Figure 119) indicate that reduction starts from *c.* 1905 at the pine tree located nearest the loch. Reductions in radial growth progressively affect pine sampled further from the shore a few years later (Figure 97 and Figure 119). The radial growth of six trees becomes too narrow to be reliably measured between 1945 and 1972. The radial growth rates of Scots pine growing on dry sites react almost instantly to changes in the local water table (Rigling *et al.* 2003). Loch Maree is known to have dramatic fluctuations in water levels that can alternately expose and cover smaller, low-lying islets (www.snh.org.uk). No quantitative data on fluctuations of water level were however identified, but North Scotland has become 21% wetter between 1961 and 2004 (Barnett *et al.* 2006). It seems reasonable to infer that a decrease in radial growth progressively effecting pine further up slope corresponds to increased waterlogging from a rise in loch level. The responsiveness of the radial growth of Scots pine growing at the edge of lochs to changes in water levels suggests its potential use in reconstructions of past lake levels.

Glen Affric lies midway between the SE and NW areas and, in terms of cross-matching, matches equally well with chronologies from both areas. Due to uncertainty of which area to categorise this site with, the chronology was not used in the regional means. However, this chronology shows good response with both temperature and NAO indices which highlights a potentially useful area between the NW and SE areas for further research. This site, however, displays the lowest formative growth rate of mineral pine in Scotland (1.03 mm yr^{-1}) which is unexplained, but might be the result of competition. There is also some question whether this could in part be the result of genetic contamination from a nearby pine stand of German origin (Ennos *et al.* 1995).

Pine at Mallaig, which is the most westerly site, show exceptionally high formative growth rate (3.83 mm yr^{-1}) and a near absence of cross-matching and climatic correlation which is unexplained. Below the altitudinal and latitudinal tree line, the growth influence of summer temperature is expected to diminish and the influence of other climatic variables, such as precipitation and competition among trees expected to increase (Fritts 1976). While its' more southerly location could be a factor in its failure to cross-match, the growth rates, cross-matching and strong correlation with winter temperature and NAO indices established from a site of Scots pine at Dimmie (90 km further south) do not support this.

4.2 Bog Pine

The characteristics of Modern Scots pine growing on peatland at the five sites: Abernethy, Eilean Sùbhainn, Pitmaduthy Moss, Inshriach Bog and Monadh Mor are discussed, and the main probable influences on the radial growth rate highlighted. With the exception of Eilean Sùbhainn none of the relative positions of trees was known which reduces some of the details on cause and effect that might otherwise have been inferred.

4.2.1 Radial growth as in indicator of water level

Although clearly an oversimplification, growth rate can be taken as an indicator of the degree of adaptation by a tree to its environment. The relationship between Scots pine and relevant environmental factors is often complicated by different methodologies between forest ecologists and dendrochronologists. Tree-ring width is the end result of site and climate interactions on tree-growth and its use in growth trend mean sequences and plots (Figure 76 & Figure 77) allow more direct comparison of growth rates (both past and present) and help bridge the gap between tree-ring sequences and forest mensuration, (mensuration means measurement of length, mass and time).

Low radial growth rates ranging from 0.5 to 1 mm yr^{-1} are seen in Scots pine growing on bog at Abernethy, Eilean Subhainn and Pitmaduthy, these compare to growth rates of ≥1.5 mm yr^{-1} on adjacent mineral sites (Figure 76 and Figure 77). These results accord with tree growth on peatlands being limited by high water table and poor nutrient status of the soil (Boggie 1972, Mannerkoski 1991). Modern experiments have shown that drainage of peatland promotes good tree growth on peat (Burke 1975, Malcolm and Cuttle 1983a, Malcolm and Cuttle 1983b, Brække 1987, Kaunisto *et al.* 1999). One of the main effects of a lower water table is to increase the availability of nutrients (Paavilainen and Päivänen 1995, Westman and Laiho 2003), but tree roots are also able to draw nutrients from a larger volume of better aerated soil, and these factors lead to an increased tree growth (Penttilä 1991, Trottier 1991).

A rapid change in the radial growth rate of Scots pine on peat is seen at Monadh Mor, where decadal radial growth rates in one chronology more than double over a period of 40 years (from 0.83 mm yr^{-1} in the 1930s to 1.95 in the 1970s), and in a second chronology more than halve over a period of 60 years (from 2.00 mm yr^{-1}in the 1930s to 0.70 mm yr^{-1}in the 1990s). Rapid and contrasting responses in two groups of trees at a single site are unlikely to be the influence of climate and are probably attributable to changes in water level between the two different sites of peat sampled at this site. A rise in water table before 1990 at Monada Mor is noted by Mackay *et al.* (1999) and the growth decreases seen in the MONM-M2 chronology appear to confirm this and might elucidate on its timing. The time for Scots pine to reach maximum growth after artificial drainage of a bog has been shown to vary, depending on site conditions, from 5 to 20 years (Seppälä 1969). Interestingly, the most sudden reduction in radial growth is shown in a chronology by pine growing on mineral substrate at Eilean Subhainn, which more than halves from 1.71 mm yr^{-1} to 0.84 mm yr^{-1} from one decadal mean to the next. Examination of the individual tree-ring series identifies that growth changes from 1.79 mm to a low of 0.27 mm between 1922 and 1932, a period of 10 years, a response time which corresponds precisely with that identified by Linderholm (1999) for waterlogging. These results support the the findings of Schweingruber (1988, 1996) that trees growing on bogs react almost instantly to changes in the local water table and can thus allow variation in tree-ring width to be used to reconstruct the ecological history of bogs.

The sites bog pine in this research showed little or no age trend, but few of the modern chronologies developed were from trees over 175 years of age. In Sweden, Ågren and Zackrisson (1990) found that Scots pine growing on peat reached their maximum height (height ≤ 10 m) after about 150 years and that radial growth slowed down above this age. The radial growth rates of bog pine over 175 years old may be found to reduce with age, although this was not seen in subfossil bog pine. Most tree species can barely survive when rings are reduced to 0.50 mm yr^{-1} (White 1998). Therefore radial growth rates of 0.5 to 1 mm yr^{-1} suggest the trees occupy a narrow window of survival. Scots pine growing on blanket bog at Strathnaver Forest since the 1952 have an average two rings missing, which similarly indicates a narrow ecological survival window on bog beyond the tree line of 58° N. The absence of the gradual reduction in ring width normally associated with age could be the result of these minimal growth conditions.

Anderson and Harding (2002) hypothesised that there is a critical threshold of disturbance or alteration below which bog woodland development occurs but above which succession to closed-canopy woodland follows. They suggest the growth and form of individual trees as the best indicators of whether this threshold has been reached: straight, vigorous growth with regular branching indicating that a site has crossed the threshold and closed canopy woodland will succeed, whereas slow, stunted growth probably indicates that a bog woodland community will persist. This is in accordance with observation of tree growth at the sites analysed, and by Daniell (1997) who found pine growing on bog at Glen Cassley (NGR NC 397 136) achieving heights and radius of 9 m and about 95 mm respectively, while 20 m high pine with a radius of about 290 mm grew on adjacent mineral surface. In the Swiss Jura, Freléchoux *et al*. (2000) found *Pinus unicinata* had existed since the development of the bog and could be considered to be climax communities, but succession in response to drainage and peat cutting had altered their distribution, with the denser types spreading inwards from the bog edges and developing near peat cuttings and the sparser types spreading onto formerly treeless central parts.

Low radial growth rate of Scots pine growing on peatland in Scotland is therefore argued to be directly attributable to the waterlogging. The results suggest a simple distinction between pine growing on active/waterlogged mire/bog/fen (bog pine) and those growing on inactive peatland can be made on the basis of radial rate of growth. A low radial growth rate of 0.5 to 1 mm yr^{-1} is proposed to indicate pine growing on waterlogged/active bog, mire or fen. With some important periods of exception (discussed further in section 4.3), the radial growth rates of subfossil pine that grew on peat are also found to be under 1 mm yr^{-1}. This rule of thumb is therefore probably applicable to most lowland and foothill sites (i.e. below 325 m). The formative growth of pine at Creag Fhiaclach is not known, but the mean ring-width from the sites indicate that on mineral substrate the radial growth rate falls below 1.00 mm/yr^{-1} from 400 m as the tree line limit is approached. A degree of caution should also be exercised in comparing modern ecological and palaeological data, as subfossil pine may underestimate ring widths due to possible diagenetic changes. However, from the author's experience, modern cores and sections are far more prone to slight shrinkage than subfossil pine.

4.2.2 Disturbance History

The earliest communities of bog pine at Abernethy (site B) and Eilean Sùbhainn (site B) are shown to have established themselves from the 1780s with later sites in the area developing in the 1830s and 1860s respectively. The bog pine at Pitmaduthy germinated in the 1880s. The chronologies from these three sites have mean ring widths of 0.44-1.00 mm yr^{-1} and are considered to represent mature bog pine woodland. However, gradual changes in radial growth indicate that they have all undergone some disturbance (with the possible exception of site A at Abernethy).

4.2.2.1 <u>Peat cutting</u>

The precise location of the pine sampled from Monadh Mor and Inshriach in not known, but the trees at both sites germinated relatively recently, in the 1900s and 1940s respectively. A formative growth rate of 1.85 mm yr^{-1} for the samples forming the chronology MONM-M1, which reduces to 0.94 mm yr^{-1} in the 1980s (Figure 77) suggests that these pine germinated on peat that subsequently became more waterlogged. A water table rise, the cause unknown, is described to have led to paludification of a wooded area of the mire before 1990 (Mackay *et al.* 1999). Similarly at Inshiach, the high formative growth rate of 2.89 mm yr^{-1} (Figure 77) suggests that pine germinated on peat rather than active waterlogged bog. Anderson and Harding (2002) describe the Scots pine at Inshriach as “markedly stunted”, but the samples measured from this cut-over peat have comparatively high formative growth rates of 2.89 mm yr^{-1}, well above those for pine growing on adjacent mineral substrate (Figure 76). These trees also show a reduction in growth consistent with age trend, a characteristic otherwise absent from the sites of bog pine sampled (Figure 148). Conversely, a second group of trees at Monadh Mor which formed the chronology MONM-M2 have a decadal growth rate of 0.83 mm yr^{-1} from their germination in the 1930s which then progressively increases to 1.95 mm yr^{-1} in the 1970s (Figure 141). This suggests pine germination on active bog, but that there was a subsequent lowering of the water table, possibly caused by peat cutting.

The chronologies established from Inshriach and Monadh Mor suggest these sites have undergone considerable disturbance and are therefore useful to help establish some of the characteristics of pine response to changes in bog status. The samples from Inshriach were taken on a transect which followed a gradient from a peat cutting face to the bog centre. The three samples which cross-matched to form the site chronology at Inshriach probably germinated on a less waterlogged surface caused by the peat cutting, the failure of the other seven samples to cross-match seems likely to be due to changes in waterlevel associated with different distances from the cutting. Schulthess (1990) found trees growing 250 m from ditches were not affected by drainage. The failure of the MONM-M1 and MONM-M2 chronologies to cross-match is likely to be attributed to differences in the status of the peat substrate and ongoing changes, again probably associated with peat cutting. These findings support those of stratigraphic analysis by Wells (2002) that the bog woodland communities at Monada Mor and Inshriach are relatively recent developments on previously cut-over mire.

Scots pine at Inshriach which germinated *c*. 1942 was probably able to do so quickly, seeded from forest which grows adjacent to the site. Peat has long been used as a fuel. It is speculated that the exceptionally cold winters of 1940-42 might be linked to the last cutting of the cutover peat surface at Inshriach and led to conditions on peat favourable for the natural germination of pine. It has been speculated from Modern forestry studies that two consecutive summers warmer than the “average” are required for the regeneration of pine in the forest-limit zone (Sirén 1961) and pointer year analysis indicates years 1943, 1944 and 1945 as favourable for pine in the South-east region. A combination of these factors could account for the germination of pine on cutover peat at Inshriach.

4.2.2.2 Scars

Only three percent of samples from both modern trees and subfossil, sampled predominantly by coring and full sections respectively, contained scar information. These low recovery rates highlight the rarity of scar information and perhaps also explains its limited use in relation to mammals. Since Spencer (1964) first used dendrochronology to examine populations of Porcupine (*Erethizon epixanthum*) through their feeding on the phloem layer of Pinon pine (*Pinus edulis*), few workers appear to have considered the scarring of trees by mammals. Here, a tentative method to differentiate between scars likely caused by mammals and those caused by fire is based on research that all pine with less than a 5 cm diameter (assumed to be 4 cm without bark) died as a result of fire (Kolström and Kellomaki 1993). Due to the scarcity of scar data, both modern and subfossil pine are considered. Lageard (2000) interprets firescars in four subfossil pine samples with diameters between 2.4-3.3 cm, but without regard of scars from mammals, so whether the rule can be applied to bog pine is debatable. Nevertheless, a sampled fire scarred tree at Abernethy with a diameter of 3.8 cm (without bark) is taken as support for the lower limit for the survival bog pine from fire. Scars in trees below 3.8 cm diameter are therefore considered likely to be caused by mammals.

The earliest trees sampled at Abernethy germinated *c.* 1694, but until *c.* 1850 there are probably too few trees for either mammal or fire scars to be identified through the core samples from these sites. Even the scars caused by low to moderate intensity fires readily overheal and are difficult to detect (Zackrisson 1980). Nevertheless, the data indicate that over the 150 year period 1850-2000 only two fires, in *c.* 1887 and 1920 affected this bog pine site. One mammal scar is identified to occur late in 1816 in a pine with a diameter of 1.7 cm (without bark) at Abernethy. The scar data for Eilean Subhainn indicates that over the same 150 year period 1850-2000, two probably widespread fires occurred at this bog pine site in 1923 and 1961. Observations indicate that a more recent fire in the neighbouring mineral substrate pine did not advance more than a few meters onto the mire surface, which is in agreement with Pitkänen *et al.* (2001) and Turunen *et al.* (2001). Germination is commonplace thoughout the period 1800-1950 at both Abernethy and Eilean Subhainn and the pine at these sites do not display the abrupt radial growth release characteristic of trees breaking though the browsing limit, in an area of intensive deer browsing (Vila *et al.* 2003). Therefore, although the presence of mammals is indicated at Abernethy, it is not considered a factor limiting the colonisation of pine at either bog site between 1800 and 1950.

Eight fire scars show mean reductions of 23% over a 2 year period and 31 % over a 20 year period in the subsequent radial growth of Scots pine. This response to fire contrasts with findings by Lageard (2000), who in the two years following fire identified average increases in mean ring width of 0.92-2.74 mm in fire-scarred subfossil Scots pine trees from England. The different response may be primarily one of methodology. Lageard compares subsequent growth to the ring in which the scar occurs. This is considered to bias subsequent growth to show increase, particularly in the case of early season fires. Differences in the season of fire might also account for a difference due to early season fires tending to lead to narrower rings, and late-season-fires wider rings, in the subsequent 1-3 years of modern pine on a mineral substrate (Drobyshev *et al.* 2004). Individual ring width plots clearly show however that while some trees show increase, others show a decrease, in the subsequent radial growth response to a fire and therefore larger samples (preferably of full sections) appear desirable to more fully establish the responses of bog pine to fire.

Reductions of ≥15% over both 2 year and 20 year periods seen in the radial growth of both the site mean and a neighbouring chronology for the fires in 1920 at Abernethy, and in 1923 and 1961 at Eilean Subhainn suggest they were widespread. Although forest fires are thought usually only to advance a few metres on the mire surface (Pitkänen *et al.* 2001, Turunen *et al.* 2001), during periods of drought fire is able to advance onto mires (Pitkänen *et al.* 2003). The bog pine sites at Abernethy and Eilean Subhainn identify two fires over a 150 year period between 1850 and 2000. Although not a direct comparison, an average fire interval of 170-240 years at one Holocene pine site has been identified (Pitkänen *et al.* 2003).

The reductions in pine growth are in accord with recent high-resolution stratigraphical analysis carried out in boreal bogs of Europe, which show that fires can influence the past mire-surface moisture conditions and that they may explain many episodes interpreted as wet in the past i.e. (Tuittila *et al.* 2007, Sillasoo *et al.* 2007, Väliranta *et al.* 2007). Three ways by which fires could alter moisture conditions are proposed. Where mire are not omprotrophic fire in the surrounding marginal area can change evapotransiration and run-off regimes resulting in a general rise in water level. On bogs, deep combustion might lead to a local hollow formation. Damage to vegetation caused by widespread fires may also reduce rainfall interception and transpiration. All three mechanisms could lead to increasing water levels and causing the reduction of radial growth in pine. Heather (*Calluna vulgaris*) has a slow (10-60 year) recovery period after fire (Schimmel and Granström 1991). Scots pine intercept up to 30% of rainfall (Hornung and Newson 1986), and so those trees damaged or killed by fire could also have decadal effects on water table. Paradoxically, the 20 year plus reductions of radial growth observed in pine growing on mire after a fire may well be the result of an increase in water levels and drowning. If damage to vegetation by fire is a mechanism for increasing water table, the fires in *c.* 1887 and 1920 at Abernethy may have a cumulative effect on the reduction of radial growth in pine.

4.2.3 Climatological influence

Correlation function and moving correlation functions identify that the monthly relationships with climate, most commonly seen in pine growing on mineral substrates (e.g. positive responses with January/February and July/August temperature, and a negative response to August precipitation) are predominently absent in pine growing on peat in northern Scotland. The difference is clear even where chronologies are developed from peat and mineral substrate sites immediately adjacent to each other, such as at Abernethy. In this respect these results are similar to those obtained in previous investigations in Europe (Lundh 1925, Läänelaid 1982, Vaganov and Kachaev 1992, Linderholm 1999, Linderholm 2001). However, in Scotland, two relationships of monthy climate with the radial growth of pine on peat are found between sites:

- Two chronologies at Eilean Subhainn, one from Pitmaduthy and one from Monadh Mor show a positive growth response with temperature in October. This response is similarly evident in pine growing at three mineral substrate sites at Eilean Subhainn, Loch Maree and Shieldaig. Four of these chronologies are of sufficient length for moving correlation functions to identify that this monthly response developed from the 1920s. All the sites showing this relationship are low altitude and either Hyperoceanic or Euoceanic. The response is consistent with higher temperatures and a maritime climate, allowing the development of the annual ring to continue into October. These findings are in accord with those of Schweingruber *et al.* (1979) who identified a longer growing season for Scots pine in western Scotland and Barnett *et al.* (2006) who identifies that the length of growing season in Scotland has increased by more than 4 weeks since 1961.

- Two chronologies at Eilann Sùbhainn and one from Abernethy show that winter NAO indices in February have a positive influence on pine growth. This response is evident in pine growing at seven mineral substrate sites (four in the north-west and three in the south-east areas). Two mechanisms for this response have been proposed (see section 4.1.2). Scotland's mild winters (in terms of temperature) may allow winter photosynthesis and/or winter gales (which again may lead to warmer weather) may lead to loss and damage to needles/branches/tree thereby reducing radial growth that year. All the sites showing this relationship are exposed (either high altitude or near the coast or both), which indicates that winter gales causing damage to the tree could be a factor.

4.2.3.1 Does pine on dry peatland respond similarly to those on mineral substrate

Joensuu (1984) found the drainage of bog alters growth conditions to resemble those of mineral substrate, therefore one might expect the climatic response of pine growing on drained peat to become similar to those growing on mineral substrates. There is some supporting evidence for this change of response from three sites in this research. At Monadh Mor, the MONM-M1 chronology is the only one developed from peat pine found to have a climatic relationship with a month commonly identified from pine growing on mineral substrate. The pine have a formative radial growth rate of 1.85 mm yr^{-1} indicating that they were not restricted by waterlogging, the MONM-M1 chronology shows a positive relationship with August temperature. Although the chronology at Inshriach was too short to conduct correlation function analysis, its formative radial growth rate of 2.89 mm yr^{-1} indicates that the pine growth is not restricted by waterlogging and it cross-matches well (*t*-value 5.2) with neighbouring pine growing on a mineral substrate. Conversely, pine growing on the loch shoreline at Eilean Subhainn (with low radial growth suggesting it has been restricted by waterlogged conditions from 1905) provides evidence that the climatic response of pine growing on a waterlogged mineral substrate closely resemble that of bog pine. The ESDG-13 chronology cross-matches well with its neighbouring chronologies that grow on bog and correlation functions show a common response to monthly temperature in October.

The chronologies at Eilann Sùbhainn and three at Abernethy developed from pine growing on a peat substrate are well replicated and cross-match well within their respective sites, but fail to cross-match together. This apparent failure of regional cross-matching between the chronologies developed from bog pine might suggest that radial growth responds more to local site conditions than to a common climatic signal. However, this hypothesis is not supported by correlation function analysis, which identifies common relationships between temperature in October between the sites at Eilean Subhainn, Pitmaduthy and Monadh Mor, and NAO indicies in February at Eilean Subhainn and Abernethy. Although only 135 km apart, the Eilann Sùbhainn and Abernethy sites are very different in climate and altitude and both have been disturbed by fire. All of these factors could be responsible or contribute to the failure of cross-matching.

A potential for regional cross-matching is however suggested by a *t*-value match of 7.7 (seen visually in Figure 83), between peat substrate pine chronologies at Monadh Mor and Pitmaduth Moss, which are some 30 km apart. The limited number of site chronologies of Scots pine growing on peat substrate clearly restricts the conclusions that should be drawn from their climatic analysis, particularly as the analysis of pine from mineral sites highlights considerable differences between sites in Scotland, even over short distances. More chronologies developed from pine growing on peat in northern Scotland are required to establish if there are common relationships with climate and how these may be changing.

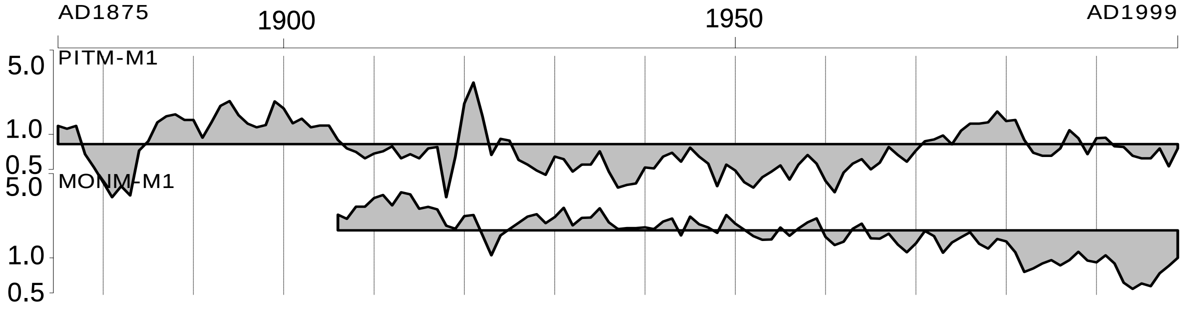


Figure 83: Ring-width plots of the sequences from Pithmaduthy (PITM-M1) and Monadh Mor (MONM-M1). The y-axis scale is logarithmic.

4.2.3.2 *Clarifying the relationships between climate, bog and pine*

The reponse of bog pine to climate change appears likely to be complex. Kilian (1995) identify the probably lag in the response of the water table to changing climate conditions. Abrupt and widespread drying of about the topmost 13 cm (*c.* 1980) of north European bogs has been inferred for replacement of species adapted to dryer conditions (Tuittila *et al.* 2007, Bosworth 2005, Gunnarsson *et al.* 2002). In northern England, Charman (2007) found short-term high-frequency changes in reconstructed water-table records to have a linear response with annual rainfall deficit over the previous 5-10 years, but suggests long-term climatic wetness may have caused a general rising water-table that occurs over the nineteenth century. Charman considers this to culminate in a step shift to a wetter mire surface around the 1900s. A change in the reponse of pine growing in both mineral and peat substrates to monthy climate data which occurs from the 1920s (see section 3.4.3), provides added evidence for a shift possibly to generally wetter mire conditions around this period.

Linderholm (2001) suggests the combination of the direct effect of temperature together with delayed effect of climate on water table variations and decomposition of peat as likely to dilute the annually resolved climate information in tree-rings. Additionally, it is important to understand that once germinated on a peat surface, pine trees themselves intercept rainwater and increase the rate of evapotranspiration, thereby tending to lower the watertable and dry the surface (Anderson 2001). They may also trap particulate material from the atmosphere and increase the rate of nutrient input to these inherently nutrient poor systems (Schauffler *et al.* 1996). The influence of trees on a bog's microclimate is profound, particularly in terms of the canopys inception, when up to 30% of rainfall never reaches the bog surface (Hornung and Newson 1986), and trees also considerably interrupt airflow. The implications are that the presence of pine themselves on a bog will tend to lower water table and increase their growth rates. The degree to which this effect might be expected to exaggerate or dampen tree response to a decrease or increase in rainfall respectively is unknown.

These results suggest bog pine may have a critical role in helping to establish the relationship between water table in mires/bogs and climate. Accumulation rate and stratigraphic relationships of peat with pine preservation remain poorly understood. Evidence from north European bogs generally supports the concept that shifts in wetness dynamics are often individualistic in each site and can be weakly connected to general climate systems (Väliranta *et al.* 2007), therefore analysis of pine in additional types of mire sites is likely to be required before the relationship between the moisture records in mires and climate are more fully understood. Using humification analysis, Binney (1997) identified variations in upland blanket mires between the climatically contrasting NW and SE areas of Northern Scotland which suggested degrees of "sensitivity" and "complacency" in different peat profiles, which highlight an area for research. Charman (2007) suggests regional abrupt shifts in bog surface wetness interpreted as abrupt shifts in climate may also be generated by periods of increased wetness over longer periods.

4.2.4 Prospect for further reseach

This research indicates that in the past pine has been sensitive to changes in climate. A possible altitude increase in tree line has occurred (French *et al.* 1997) and it might be considered useful therefore to monitor the extent and growth rates of pine on mire and bog surfaces beyond the latitude of 58º North. The relationship between peat accumulation rates and the occurrence of pine are highlighted as an area requiring further research. Because of the sensitivity of bog vegetation to water level changes, regional variations in the radial growth rate of pine growing on peat may reflect overall shifts in evapotranspiration. Comparisons between proxy-climate reconstructions, instrumental climate data and tree-rings from *in situ* trees provide the potential for calibration of pre-instrumental proxy records. At Hanvedsmossen in Sweden, Linderholm (1999) undertook dendroclimatic analysis of Scots pine growing on a bog site today, where subfossil pine had also been recovered, and such an approach in Scotland might also be considered useful to compare the past and present conditions allowing the growth of pine. This might be usefully combined with proxy-climate reconstructions and tree-rings from *in situ* subfossil trees (particularly pine in Scotland) to extrapolate outside the range of instrumental record values. Few studies have investigated peat profiles in relation to Modern trees and the *in situ* remains of subfossil pine. Such research is suggested to help calibrate our understanding and the timings of peat moisture regimes, accumulation rates and pollen. Britain contains 10-15% of the total global area of blanket bog (Lindsay *et al.* 1988) and this line of research could also be potentially applied to two other tree taxon in the UK, which are also preserved in Holocene peats – oak (*Quercus* spp.) and yew (*Taxus* spp.).

Knowing the location of pine sampled at the edge of Loch Maree on the island of Eilean Sùbhainn was useful to help interpret the loch level progressively rising up slope (Section 4.1.5). Pine growing at the edges of lochs in Scotland may be useful in reconstructing past loch levels, but should perhaps be avoided when sampling to establish the relationship of pine with climate. It would be useful to sample pine growing on mineral substrate on the island, to establish a direct comparison climatic response. Recording the location of individual pine sampled for dendroclimatological analysis is suggested as useful, particularly so in further research on bog pine, where it may be important in helping to identify fluctuations in water levels.

4.3 Holocene Bog pine

Although in the terms of dendrochronological dating the WRATH-9 chronology fails to date, tentative cross-matching at 3139-2910 BC for the shorter WRATH-9ED chronology is consistent with radiocarbon dates. The failure of the longer WRATH-9 chronology suggests that some problems have yet to be resolved, which is why the spanning of events is discussed mainly in terms of relative years (RY). Nevertheless the *c.* 3175-2790 BC span of the full WRATH-9 chronology (*c.* is normally used in terms of dendrochronology to indicate within just a few years of) highlights the potentially huge improvement on resolution compared to other data. Hitherto Scots pine growing on mire in Scotland has been indicated as rarely capable of intersite cross-matching. The cross-matching of 49 component sequences from 9 sites provides good evidence that the trees were responding to a sufficiently strong common climatic signal. Their cross-matching allows an unprecedented examination at annual resolution over the region: how and why *P. sylvestris* expanded, retreated and became preserved in the peatlands of the far north of Scotland. The implications of these results on factors of colonisation and preservation are further considered.

4.3.1 Problems of dendrochronological dating

Precisely why the WRATH-9 chronology should fail to date is unclear, but three main reasons that are not mutually exclusive are considered:

- missing rings in the first and end 50 years of pine growth
- variation in water level over mire, leading to different responses of pine to climate in different positions.
- a strong regional response to climate may be limited except during relative dry periods (as indicated between RY50 and RY200).

Problems in the less well replicated beginning and end of its component chronologies, as well as possibly the reference chronologies for Scots pine during the mid-Holocene, are considered most likely for the failure in dating the WRATH-9 chronology. Extremely narrow rings exist in many subfossil pine reference chronologies. Interestingly the problem in the end section of WRATH-9 begins at a sharp reduction in growth in the chronology from Ballymacombs More (a component of the PINE3000 chronology) which occurs in 2910 BC (Figure 84). Missing rings in the first and end 50 years of pine growth, where growth rates fall in consecutive years to below 0.2 mm yr^{-1}, are identified in both subfossil pine and modern pine growing on mire through the course of this research. Scots pine from an area of blanket peat in the Strathnaver Forest shows an average of two rings are missing over the first 40 years of pine growth (Section 3.1.9.3). Other studies of subfossil pine have also shown low correlation between trees growing at single sites (Bridge *et al.* 1990, Pilcher *et al.* 1995), which may also have been in part due to these problems. These problems emphasise the importance of replication of data in tree-ring analysis, both in cross-matching and establishing chronologies.

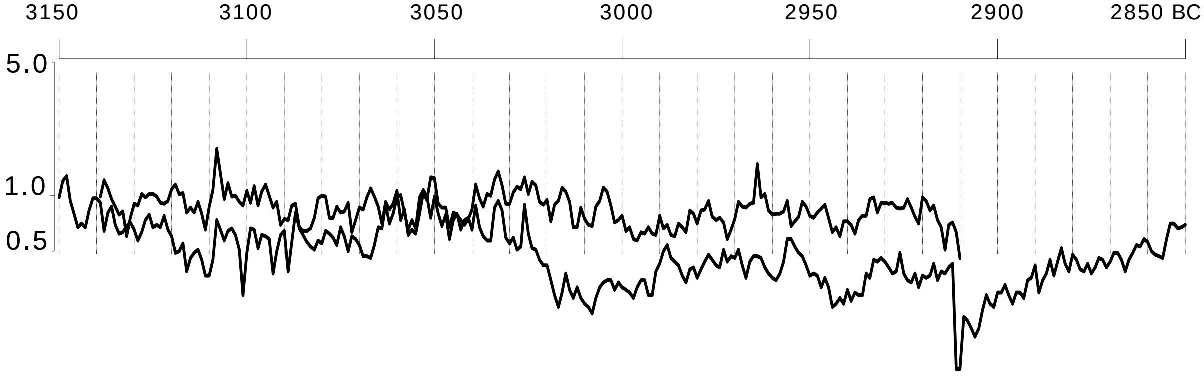


Figure 84: Ring-width plot showing the close match between the sequences WRATH-7ED (upper) and PINE3000 edited to span 3150-2850 BC (lower), which cross-match with a *t*-value of 5.7. Ring width (mm) is plotted on a logarithmic scale on the y axis, using a common axis.

The cross-matching of the Badanloch and Loch Vatachan chronologies with WRATH-7 and its component chronologies is well replicated. This indicates that earlier dating of the Loch Vatachan chronologies (Daniell 1997) was probably erroneous. Filtered versions of the full Loch Vatachan and Loch Shin chronologies were stated to cross-match with a *t*-value of 6.34 (Daniell 1997), and therefore Loch Vatachan chronology was dated to range from 3405 to 3231 BC (Daniell 1997). Raw tree-ring values for these two chronologies give a *t*-value of 6.38 at the same relative position. However, slightly shortened edited versions of the chronologies VATCH-ED and SHIN-ED, fail to cross-match. Only 14 years were removed from the end of VATCH-ED, which is dated within the WRATH-9ED chronology to span 3159-2999 BC. This new date suggests that the earlier date was spurious. A ^{14}C sample (SRR-5814), taken from rings 37-73 of the original Loch Vatachan site chronology, produces a date of 4570 ± 45 uncalibrated ^{14}C yr BP. On calibration this date gives an estimated age range of 3500-3100 ^{14}C cal. yr BC, which could equally apply to either of the dendrochronological dates indicated. A strong regional response of pine growing on peat to climate may only occur during relatively dry periods, (i.e. between RY50 and RY200 when increased radial growth rate suggests lower waterlevels). The reponse of Modern pine growing on peat in north Scotland (section 4.2.3.1), provides some additional support for this. All three areas will require further investigation to further understand the failure to date the WRATH-9 chronology.

4.3.2 Colonisation

The evidence presented for an initial simultaneous regeneration of pine across a wide area of the north of Scotland is unexpected. Not only does this provide evidence of the ability of pine to take rapid advantage of advantageous changes in climate, but also that at that time a number of other factors were probably favourable for germination, and these are now further discussed.

4.3.2.1 Seed source

The cross-matching of subfossil pine identifies that pine germinated probably in the same year at four peat sites spread over an area of 60 km^2 at *c.* 3200 BC. Although the importance of dispersal is widely recognised by plant ecologists (Harper 1977, Shmida and Ellner 1984), surprisingly little is known about the process and mechanics of dispersal. Scots pine was previously known to be a major wind-dispersed taxon, but its seeds are quoted as usually found within 100 m of source (McVean 1963b, French *et al.* 1997). Smith (1900) and Carlisle (1968) record distances of about 800 m. If pine is restricted to short distance distribution of seed, this would suggest that pine must have been growing on mineral substrates local to the subfossil pine sites in this research before *c.* 3000 BC. It is considered unlikely that pine could have been widely present over the northern Highlands of Scotland before *c.* 3000 BC, undetected by pollen analysis. However, small numbers of pine trees growing in sheltered valleys and niches (as seen today in Figure 9) remains a possibility. Nevertheless, McVean (1963b) identifies seeds could be carried much further in gale-force winds and found saplings in the Cairngorms more than 2 km from the nearest living tree. French *et al.* (1997) also found a maximum dispersal distance of 3.2 km from a forest line, where sapling density reached about 3 ha^{-1}.

To help identify whether pine is likely to have already been present locally at *c.* 3000 BC, the potential of pine seed to disperse over a wide area is assessed, using a simple ballistic formulation (Pasquill and Smith 1983):

$$x = Hu/F$$

where x is the predicted horizontal distance from maternal parent to deposition site, H is the release height above ground, F is the constant descent velocity, and u is the horizontal wind velocity. A mean terminal velocity of 0.74 m s^{-1} which has been calculated for pine seed (Debain *et al.* 2003) was used in this formula to make the following estimates (Table 22).

Table 22: Estimated potential seed dispersal distances of Scots pine

Wind event	Wind velocity (m/s)	Release height (m)	Predicted seed dispersal distance (km)	Release height (m)	Predicted seed dispersal distance (km)
Gale	17.4	20	0.5	600	14.1
Storm	24.7	20	0.7	600	20.0
Hurricane	32.9	20	0.9	600	26.7
Gusts	46.3	20	1.3	600	37.5
Max lowland	77.2	20	2.1	600	62.6
Max highland	83.1	20	2.2	600	67.3

Note: The release height of 20 m represents an average height tree of *Pinus sylvestris*. A height of 600 m represents a tree growing at tree-line in the Cairngorms today.

These estimates are simple in comparison to a formula by Greene (1989), which takes account of the aerodynamic properties of pine seed and therefore the present formula

probably underestimates the predicted dispersal distance of seeds. However, the estimates of
Table 22 illustrate the potential for gusts and extreme winds to disperse seeds from Scots pine growing on mountains over long distances to rapidly colonise wide areas. These figures indicate that Scots pine, growing on Beinn Dearg in the Torridon mountains (which is currently within the current treeline), have the potential to colonise the most northerly site of subfossil pine sampled, Polla on Loch Eribol 70 km to the north.

Long distance (about 60 km) dispersal of Scots pine seed by gusts provides a simple mechanism by which the species is able to take advantage of perhaps short periods for the colonisation of a bog surface, that species such as oak cannot. Pine's requirement for good light also means that in the longer term it is less able to compete with oak. These mechanisms appear useful to help explain the temporal segregation of subfossil oak and pine observed in some bog environments further south (Chambers *et al.* 1997b). While contemporaneous phases of subfossil pine and oak on mires such as those identified in Ireland and the Midlands could be explained by the succession of oak, or human interference and/or stochastic disturbance events, as also suggested by Miles (1988). The potential for Scots pine to colonise long distances can also be reconciled with estimated migration rates of at least 1.5 km yr^{-1} during the Late-glacial period from pollen analysis (Huntley and Birks 1983). Assuming an age of 20 years for trees to start producing cones, with this delay between germination and seed production, to achieve the rates indicated during the Late-glacial period, pine would be required to disperse seed over 30 km. This distance of seed dispersal is not irreconcilable with those predicted with wind speed from storms (Table 22). Therefore, the average yearly migration rates for Scots pine would remain unchanged, although an erratic jump colonisation mechanism through the long distance transport of seeds by high winds is hypothesised.

4.3.2.2 Bog surface conditions for germination

Waterlogged seeds fail to germinate and the results of modern studies on peatland indicate pine recruitment may be expected to be primarily determined by groundwater levels. The wettest part of a natural bog other than the surrounding lagg fen is generally found on the highest part of the dome, which usually contains more than 90% water by weight (Hobbs 1986). Bragg (1982) demonstrated that over the central area the water table resides within 5 cm of the annual mean water level for more than 95% of the year and that all components of living vegetation lie within 25-30 cm of this very stable water table. In the event of a lowering of the water table, one would expect drying and hence germination of pine to occur first at the edge of a bog. While no relationship between germination and location was observed this is thought likely to be the result of the limited number of samples.

The possibility of a relationship between volcanic ash and the decline of Scots pine has been the topic of keen debate since Blackford (1992) identified a volcanic ash layer, (dated by Hall *et al.* 1994) to 3310 ± 10 cal. BC), that apparently coincides with the abrupt decline in *Pinus sylvestris* pollen frequencies in northern Scotland. However, a possible relationship between volcanic ash and pine germination has to the author's knowledge not been examined. Volcanic ash has two characteristics which suggest it might be significant for the germination of pine on a bog surface:

- Bogs are usually very nitrogen and potassium deficient and the phosphates contained in volcanic ash could enrich a bog
- Heather competes with pine and produces inhibitors of the mycorrhizae that help young seedlings, and ash fall could cause dieback in existing vegetation

It is therefore speculated that seasonal summer reduction in watertable causing an increase in peat crags, together with the deposition of a phosphate rich volcanic ash and disruption of the existing layer of vegetation, might re-create conditions for germination used by forestry to increase the range of pine. Possible coincidence between tephra and pine are further discussed in section 4.3.6.3.

From the initial germination of just four trees at RY1 (*c.* 3200 BC) at the four separate sites, growth is remarkably slow and no other germination is identified for the 1st 30 years, this suggests initially marginal conditions for the growth of pine on bog. However, subsequently the majority of pine germination including at another four sites, occurs in an extended 40 year phase. This is consistent with the 20 year germination lag and 20 year extended recruitment phase identified in modern studies (Edwards and Mason 2006, Ågren and Zackrisson 1990) and identifiable from subfossil pine in the White Moss chronology dated 2881-2559 BC (Lageard *et al.* 1999).

Radial growth rates above 1 mm yr^{-1} between RY90 and RY110 coincide with the first appearance of pine in probably a simultaneous initial pulse of germination at the highest altitude and most northerly sites sampled. During this same period, second pulses of germination are also evident in two of the lower altitude sites, and this evidence is taken to indicate that optimal conditions for both the growth and germination of pine on peat were attained during this brief 20 year period. The last germination of two pine trees at separate sites is close to the second period of growth above 1 mm yr^{-1} (between RY160 and RY180) and tentatively suggests the possibility of a final third pulse of germination. However, the period between these two periods of optimum growth is too short and the germination of these two trees could equally be extended recruitment from the earlier phase.

The first mortality of a pine tree in this cohort occurs 197 years after the first germination (Figure 79), coinciding closely with a downturn in growth at all sites and the apparent total loss of pine from the most northerly site. Absence of germination, the occurrence of minimal growth rates in trees at six sites, combined with two particular episodes of mortality between RY240-250 and RY290-300 (Figure 78), provide clear evidence for a regional downturn in the conditions of growth for pine on bogs. This coincides with evidence from other workers that shortly after its expansion to northern Scotland, pine failed to regenerate (Gear and Huntley 1991, Huntley *et al.* 1997, Tipping *et al.* 2006). The close timings and regional extent of changes in the germination, radial growth and mortality rates of this sample of Scots pine provide strong evidence for cause by a regional change in climate. From the study of Scots pine growing on peat today, changes in water level is the most likely attributed cause. After RY300 there are considered too few samples and sites to identify regional patterns and infer climate change.

4.3.3 Life span implications

This analysis indicates that during the probably *c.* 3200 BC Scots pine expansion in northern Scotland, mires were occupied only for a single generation. Sites can be broadly divided into short and long term corresponding to those with trees of mean ages between 90-190 years (six sites), and 230-250 years (three sites) respectively. Commonly, a mechanism of competition for light has been invoked as an important factor limiting the process of germination. While, in nutrient-poor environments, where the canopy never closes, established trees have been suggested to suppress seedlings' growth through root competition (Chapin *et al.* 1989). Negative association between the presence of roots from adult pine and the abundance and growth of young pine has been demonstrated (P'javcenko 1960). Suppression of further regeneration by established pine could be an important factor in the structure of pine populations on bog and mire. However the briefness of the period favourable for germination in the past does not allow these factors to be properly assessed.

The two oldest subfossil pine identified in this analysis are 354 and 338 years old from Polla on Loch Eribol and Strath Canaird respectively. These compare to 363 years and 368 years for the oldest trees probably of the same period[2] found at Loch Vatachan (Daniell 1997) and Loch Farlary (Tipping *et al.* 2007b) respectively. Although of an earlier period, an about 400 year old tree from Rannoch Moor (Bridge *et al.* 1990) appears to be the oldest subfossil pine recovered in northern Scotland. This study at Rannoch Moor identified that of a 131 subfossil pine sampled from a discrete single layer at Clashgour, only 5% had more than 175 rings and 70% had less than 125 rings. In England, the oldest pine in subfossil pine chronologies at White Moss (Lageard *et al.* 1999) and Hatfield Moor (Boswijk and Whitehouse 2002) are about 200 and 336 years respectively. In Ireland, two pine trees, one dated in the Sluggan bog chronology, reached about 425 years of age, and one undated reached about 450 years. The implications are clear that while Scots pine growing on bog in the UK has the potential to live for up to 450 years, age over 300 years is rarely achieved. This is in agreement with Tallis (1983) and Paavilainen and Päivänen (1995), who state that waterlogging generally means that peatland trees rarely achieve great age.

Obviously the mortality of an individual pine need not be due to climatic change, as McVean (1963b) indicates a single wet season may be sufficient to kill pine growing in a situation marginal to their survival. Conversely however, the results of this analysis identifies this regional climatic downturn rarely rapidly killed all the pine growing over each site. This indicates larger sample sizes of subfossil pine population may therefore be considered desirable to identify climatic change during the Holocene in dendroclimatic research.

4.3.4 Taphonomy

It is important to appreciate that the presence of pine within peat is determined by the conditions of preservation rather than indicating the abundance of trees. The presence of macroscopic pine indicates its presence with certainty; however, its absence from other horizons in a stratigraphy has not previously been taken to be indicative of its absence. The water table of bogs and mires are related to their size, type and relative position, therefore these factors are important when considering changes in water table from the analysis of pine trees growing on or preserved in peat. While probably too few samples have been cross-matched in this study to identify clear relationships between stump height and peat accumulation rates, and root depth and water levels, such relationships are considered likely.

4.3.4.1 Stumps and Trunks

There is little information about the trees' form when it lived due to virtually all subfossil pine samples being recovered from root buttress level. Occurrences of trunks preserved in Holocene peat in Scotland are rare. At Loch Glascarnoch, Daniell (1997) compared a single stump with its trunk and found that they gave much the same environmental information, although the sensitivities were much the same. Slight differences in emphasis were attributed to stress on the root buttresses in stumps adding a certain amount of extra noise to the environmental signal.

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[2] The oldest tree at Loch Vatachan could not be cross-matched with the site chronology, probably due to extreamly narrow radial growth for the last 150 years of its life.

Seven trunks were recorded in this study: three at Druim Bad a' Ghaill (one containing 127 rings, the others unknown numbers of rings), three at Loch Assynt (containing 101, 127 and 189 rings) and one from Loch na Thull (containing 174 rings). However, as none of these samples cross-matched they cannot be positively identified as contemporary. Other workers on subfossil pine have identified trunks: one 6 m long on Lewis (1984), one straight 5m length of 40 mm radius at Badanloch along with a 2 m length of 35 mm radius at Meall a Gruididh (NGR: NC 531 039) (Daniell 1997) and one of about 5 m length and 80 mm radius containing 78 rings at Loch Vatachan (Lamb 1964b). The scarceness of pine trunks preserved in peat supports Rigg's (1931) observations from modern trees, that windthrow is extremely rare on bogs, at least during the periods of pine preservation during the Holocene. This is further supported by the usual occurrence of subfossil stumps; all those observed *in situ* occurred in upright positions with the roots in horizontal positions suggesting they had not experienced displacement by wind. The evidence during this period of the Neolithic does not support Lamb's (1964b) suggestion that increased storminess and wind strength impacted on trees that grew on increasingly deep blanket peat. Although not dated, recently at Loch Tulla 40 subfossil pine trunks were found that had been predominantly windthrown to the east (Tipping 2007).

Where subfossil pine is preserved, it can be said the time necessary for its decomposition was less than the time for the catotelm to encompass it. The cohort of Neolithic subfossil pine cross-matched has a mean stump height of 0.29 m. The mean accumulation rate of boreal peat has been quoted to be around 2 mm yr^{-1} (Clymo and Reddaway 1971), although average peat growth on Scottish mountain slopes appears to be slower, ranging from 0.14-0.40 mm yr^{-1} (Pears 1975, Binney 1997, Reid 2001). Charman (1994) identified an accumulation rate of 0.49 mm yr^{-1} just 10 km north of the Loch an Ruathair, which he associated with the occurrence of pine stumps. These accumulation rates indicate that it would take between 150-2000 years for a stump to be buried. The stumps of oak are reported to remain in place for up to 200 years after cutting (White 1998). Accumulation rates are considered unlikely to remain constant over this period, but the return to wet conditions suggests a period of about 150 years or less for the burial of preserved pine more likely. Rapid burial is also supported by the preservation of bark, which is now further discussed.

4.3.4.2 Bark

The year of death is an important factor in understanding the precise nature of the climatic event affecting trees. The number of rings missing from the outside of the tree may also help establish the period of exposure from death to preservation. Previous studies of pine in Scotland have only rarely found bark preserved with subfossil pine (Wilkins 1984, Bridge *et al.* 1990, Gear and Huntley 1991, Daniell 1992, 1997). This research indicates that where subfossil pine is recovered from the catotelm, bark is often present. While where pine was no longer within the catotelm and had been exposed for some time in gullies, or by water erosion, bark is usually lost. The friability of bark suggests that where it is recovered it is unlikely to have been previously exposed to aerobic conditions for long periods to time. Subfossil trees recovered from lakes, for example usually have decayed outermost rings (Zetterberg *et al.* 1994). Bark recovery is therefore another important advantage of the *in situ* preservation of subfossil Scots pine in Scotland.

4.3.4.3 Roots

Studies on modern pine on mire indicate a direct relationship between root depth and water table (Köstler *et al.* 1968). Furthermore the germination of pine itself suggests dry surface conditions are necessary as waterlogged seeds fail to germinate (McVean 1963b). A soil pit dug at the edge of a bog woodland at Abernethy identified a water table at a depth of more than 0.7 m below the surface and pine actively rooting to the same depth (McHaffie *et al.* 2002), therefore pine growth indicates that a layer of peat is aerobic The mean root depth of 45-55 cm for the subfossil pine is taken to indicate that the catotelm was beneath this level, at least during the formative growth of the tree. These depths are somewhat deeper than the results of quantitative water-table depth reconstructions for the late-Holocene in Finland which showed it had varied between 2.5-38 cm (Väliranta *et al.* 2007).

At Druim Bad a' Ghaill and Loch an Ruathair there is tentative evidence that deeper rooted trees died first which would be consistent with a rising water table. Also, although not recorded during sampling, a feature of upward bending roots was observed in several of the samples taken from Loch an Ruathair. This feature is now considered to indicate a rising water level, and the roots following the aerated surface of bogs (Leuschner *et al.* 2007). The mortality of the pines sampled at these sites occurred over periods of 80-100 years, further sampling might allow rates of water level rise to be calculated.

The dendrochronological viability of Scots pine roots has already been established (Krause and Eckstein 1994), although tree-ring profiles along roots vary much more than along trunks, the growth of roots has been found to be strongly dependent on rainfall, whereas temperature is of minor importance. This demonstrates the potential of subfossil pine roots to examine the relationship of pine with water table levels and rainfall. It also indicates that where subfossil pine stumps may have become too eroded for dendrochronological purposes, roots which might still be preserved in the catotelm could provide samples suitable for dendrochronological analysis and enable dating.

4.3.5 The probably *c.* 3200-3000 BC pine expansion and its subsequent decline

The successful cross-matching of 47% of the subfossil pine samples taken in this research strongly supports the hypothesis that the range of radiocarbon dates of about 3500-2300 ^{14}C cal. yr BC (Figure 86) above latitude 58° north in the Highlands of Scotland represented a broadly coeval expansion of Scots pine. The cross-matching of subfossil pine from 9 sites extended over the north Highlands of Scotland suggests that the trees are responding to a regional phenomenon, thought to be a climatic signal. While the WRATH-9 chronology is only tentatively dated to span 3175-2790 BC in dendrochronological terms, it is likely that the beginning and/or end are only a few years out. The results of this analysis allow us for the first time to examine the effects of climatic change on pine in Scotland during the Neolithic in terms of annual resolution. An unexpectedly rapid expansion and brief 200 year period of optimal conditions for Scots pine growth on mire is identified between RY 0-200 (probably *c.* 3200-3000 BC). The majority of mortality (73% of the cross-matched samples) occurs between RY 200-300 (probably *c.* 3000-2900 BC) during which it is assumed conditions become unsustainable for the majority of the Scots pine population growing on peat. Pine is importantly shown to be able to survive at minimal growth rates, well after conditions start to deteriorate in RY200. Of the cohort of trees cross-matched in the WRATH-9 chronology, SMUR23 was the last tree to germinate and the last tree to die in RY 165-443 (probably *c.* 3035-2757 BC) respectively. The discrepancy between the end of the WRATH-9 chronology and the year of death is due to 33 rings which were too narrow to be reliably measured. The tree SMUR23 was only 278 years old at death; assuming a maximum age of 450 years for Scots pine (see section 4.3.3), pine from this expansion could potentially survive to RY 630 (probably *c.* 2590 BC). However, the chronology developed and the maximum life span of pine identified indicates that the total episode of this expansion and subsequent decline of Scots pine in northern Scotland is unlikely to have lasted more than 450 years (probably between *c.* 3200-2750 BC). Populations decline to a few individuals that may have either been growing in slightly more favourable conditions, or else were more tolerant of the deteriorating conditions and/or did not suffer secondary stresses due, for example, to pathogens or wood-boring insects (Huntley 1997). These surviving individuals persisted for between a few decades and as much as two centuries after the death of most of the local population, although their growth rates typically was extremely low through most of this period.

Synchronicities of germination, growth rates and mortality between the subfossil pines analysed from the nine sites in this analysis across northern Scotland, provide strong evidence of climatically induced response. Further evidence for the widespread and apparent synchronous pine expansion comes from the west coast of Ireland. Ireland has a similar oceanic climate influenced by the Atlantic westerlies and like Scotland at present much of its western coastal region of blanket bog is a windswept environment unsuitable for tree growth. The mean of a close cluster of radiocarbon dates (Figure 86) from thirty nine subfossil pine covering an area of about 10 km^2 in North Mayo identify an horizon of pine which dates from 3100-2600 ^{14}C cal. yr BC (Caulfield *et al.* 1998). This is indistinguishable from a corresponding mean of 3050-2550 cal. BC from Northern Scotland pine (Caulfield *et al.* 1998). Furthermore, Caulfield and co-authors draw attention to the similarities of both expansions: sudden period of pine recruitment, followed by decline about 700-800 radiocarbon years later with a few individual trees surviving a little later. At Cadogan's Bog, in the southwest of Ireland, another colonisation by pine of mire surface is dated between 3700-2600 ^{14}C cal. yr BC (Mighall *et al.* 2004). The end of this period coincides with the dramatic pine decline of pollen in the north of Ireland, which is dated about 2600-2400 ^{14}C cal. yr BC (Mitchell 1986).

From *c.* RY180 there is no further generation, which provides evidence that conditions on the mire surface altered to suppress germination. However, with one exception, only a single extended episode of germination is identified at each of the nine sites. This is consistent with further regeneration being suppressed once a cohort of trees has monopolised available resources and a new generation of seedlings only being able to establish after members of the first cohort begin to die, making available the limited resources, as suggested by Peet (1981). A subfossil pine site in Finland identifies just four main generations of pine over a period of about 1500 years between 165 BC to AD 1400 (Zetterberg *et al.* 1994). There is insufficient evidence to indicate whether conditions are seldom favourable for germination over these periods near this forest-limit zone, or whether the initial cohort of the pine at each site restricted further germination. The evidence is overwhelming that ecological conditions required for the growth and subsequent preservation of subfossil pine coincide with periods of transition from relatively dry to wet. The widespread regional synchronicity of the preservation of the subfossil pine components of the WRATH-9 chronology in northern Scotland provides strong evidence to infer the cause was climatic change. This is further supported by the preservation of pine during this period in other areas of the UK and northern Europe.

4.3.5.1 Comparison to other pine chronologies

There is remarkable alignment between the start of Scottish pine chronologies and the start of a number of Irish pine chronologies (Figure 85). The Scottish chronologies in WRATH-9 also coincide with the largest peak of Irish bog oak and lake-edge tree populations and radiocarbon dated pine from equivalent locations. This peak in 3050 BC provides unambiguous evidence for drier conditions at this time (Turney *et al.* 2006).

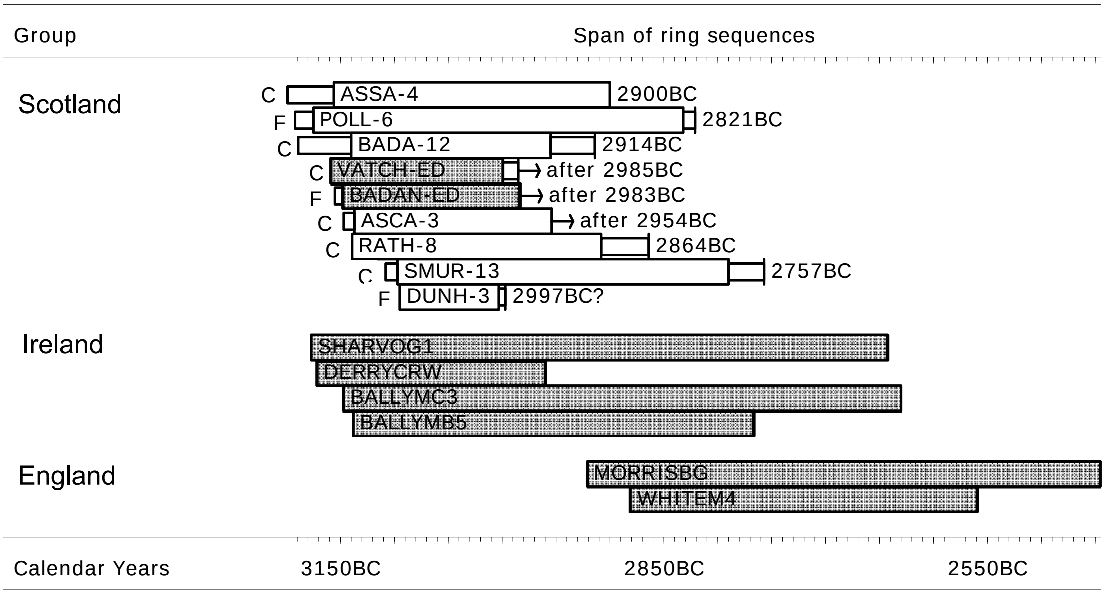

Figure 85: Bar diagram showing relative positions of pine chronologies in the British Isles and the close coincidence of starts between the Scottish and those in the north of Ireland.
C = pith, V = within 5 rings of pith, F = within 10 years of pith. The narrower bars identify approximate ring counted sections of the chonologies. The date of death of the last tree is indicated with the chronologies from Scotland. Grey bars indicate chronologies developed by other workers: VATCH-ED and BADAN-ED (edited from Daniel 1997), SHARVOG1 (pers. comm. D Brown), DERRYCRW (quoted in Lageard *et al.* 1999), BALLYMC3 and BALLYMB5 (McNally and Doyle 1984), MORRISBG (Boswijk and Whitehouse 2002) and WHITEMOSS (Chambers *et al.* 1997b).

The Irish bog oak chronology shows narrow rings between 2355-2345 BC, but interestingly, enhanced growth between 3205-3200 BC (Baillie 1995b), although soon after in 3195 BC the narrowest ring in the chronology occurs (Baillie and Munro 1988). Similarly in Ireland, a layer of silt deposited over a large area of bog between 3350-3050 ^{14}C cal. yr BC, heralds the start of widespread colonisation by Scots pine, suggesting dryer conditions (Caseldine *et al.* 2005). Previously Baillie (Baillie 1995a) outlined a “narrowest ring” methodology to illustrate the effects of extreme environmental stress on bog oaks, but this is only one aspect of the potential in subfossil wood for dendrochronological interpretation. Where absolute dates can be achieved for a wide area, detailed dendroecological comparisons potentially allow reconstruction of regional woodland response to climatic change and other environmental stresses with annual resolution.

Recent dendrochronological investigation at Campemoor, Germany, establish pine growth between 3034 to 2833 BC, and which probably extends to *c.* 2704 BC, although this later section is currently only dated visually (Leuschner *et al.* 2007). These chronologies show initial approximately 20 year phases of germination between *c.* 3040-3020 BC which coincides with a period of high radial growth rate in the WRATH-9 chronology if one assumes its dating is correct (see B in Figure 78). The start of a wet phase is identified at 2879 BC and is considered responsible for the formation of raised bogs suffocating and preserving subfossil pine (Leuschner *et al.* 2007).

4.3.5.2 Comparisons of other data

The close coincidence of the start of a number of Scottish and Irish pine chronologies (Figure 85), suggests a climatic trigger for pine germination and successful growth on peat. The subsequent preservation of the chronologies themselves within peat provides strong evidence for an increase in wet conditions. Components of the WRATH-9 chronology indicate the increase in wet conditions probably started *c.* 3000 BC. Although less precise, a number of other palaeoenvironmental records also suggest that this period was probably a time when climate changed towards generally wetter conditions:

- 3450-3350 ^{14}C cal. yr BC geographically extensive wet period (Langdon and Barber 2005)
- 3000 ^{14}C cal. yr BC – interpreted as a hydroclimatic "system switch" due to increase in frequency and severity of floods from 506 radiocarbon dated fluvial units in Great Britain (Macklin *et al.* 2005)
- *c.* 2450 ^{14}C cal. yr BC slope failure suggest relatively wet conditions (Reid and Thomas 2006)
- 2310±20 ^{14}C cal. yr BC this Hekla-4 date (Hall *et al.* 1994) is used to mark a start of wetter conditions in Scotland (Langdon and Barber 2004).

This study has already highlighted a problem in the use of radiocarbon dates in the identification of synchronous Holocene climatic event, where a *c.* 410 year occurrence and dating of pine macrofossil can only be narrowed to a range of about 1200 radiocarbon years (Figure 86). Nevertheless, the probably precise timing of this pine expansion also provides an opportunity to compare other radiocarbon dates of this event. At Cross Lochs, Charman (1994) used *Pinus* achieving 20% of total land pollen (Bennett 1984), to interpret the local presence of this pine expansion pine in northern Scotland. Pine was interpreted to be locally present over a 12cm section of the stratigraphy, which two uncalibrated radiocarbon dates (SRR-3709, 4250±45 and SRR-3708, 3920±45) bound between 2900-2350 ^{14}C cal. yr BC. The cohort of pine dendrochronologically dated indicates that regionally the majority of pollen is likely to have been produced over a 300 year period between *c.* 3150-2850 BC. The Loch an Ruathair chronology which is only 10 km south of Charman's site indicates that the majority of pine this far north may have been present for a slightly shorter 250 period between *c.* 3150-2900.

Similar comparisons between radiocarbon dated sub-fossil pine and pine pollen in stratigraphic sequences of peat are possible at a number of sites in Scotland and Ireland (Figure 87). Although the pollen analysis appears able to help identify the briefness of this pine expansion and contraction, radiocarbon dates appear to be too young by about 250 years at the appearance of pine, and by about 550 years when it became absent on peat. Though the time spans for pines probable occurrence on surrounding mineral soils which might survive and produce pollen for a longer period is unknown. The evidence supports that of other workers in Scotland, who have found the radiocarbon dates of peat to be 300-700 younger than those produced from wood. The northern pine expansion has been identified over short lengths of stratigraphic section 12 cm (Charman 1994) and 1.5 cm (Gear and Huntley 1991) and it is possible for pine to have had short lived occurrences but remain undetected in the pollen stratigraphy due to it falling between samples. The downward migration of pollen has yet to be evaluated and could be another factor for error.

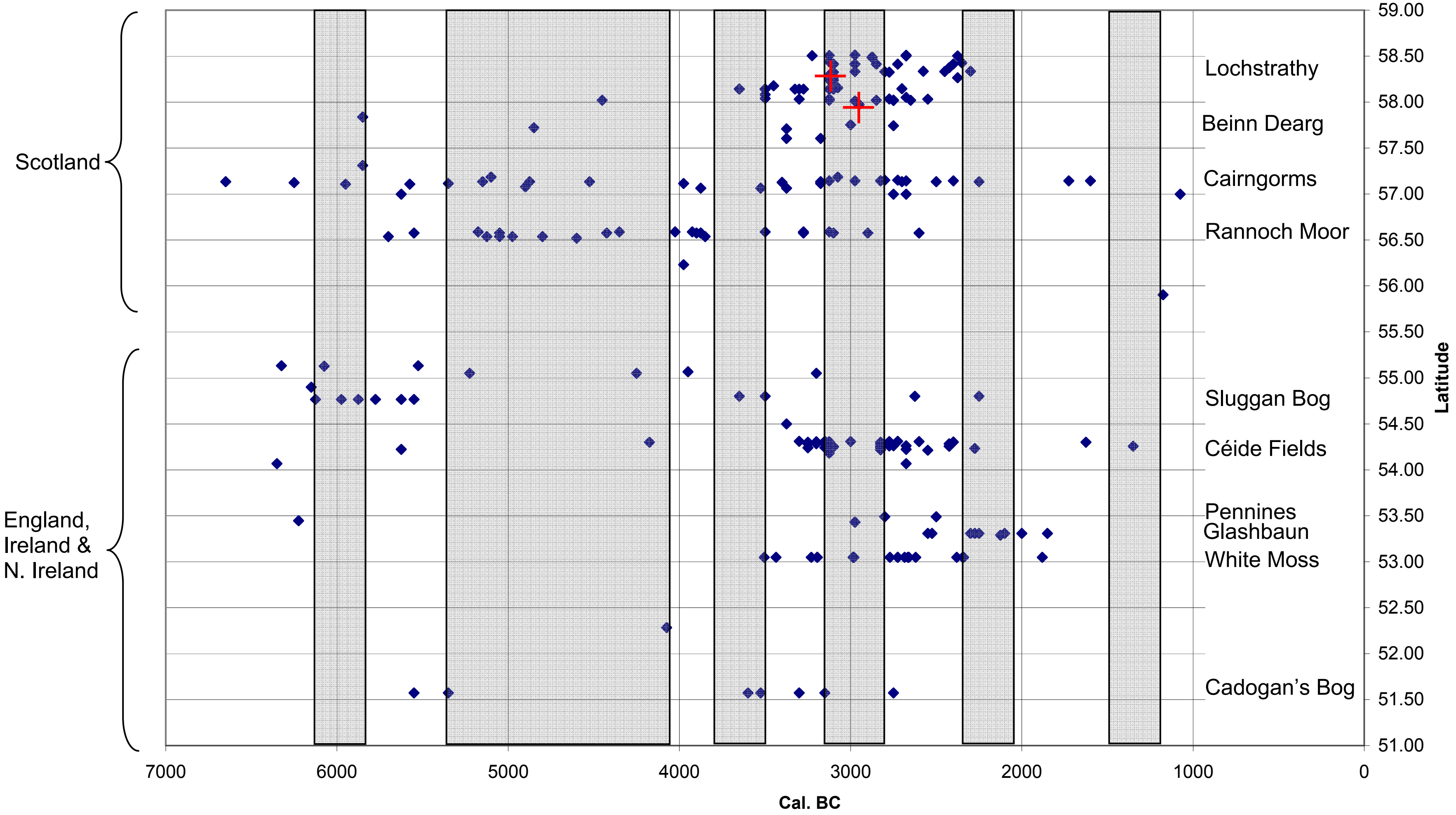

Figure 86: Radiocarbon dates over the range 7000-1000 ^{14}C cal. yr BC for Scots pine at different latitudes in the British Isles with some of the larger study area identified (mid-points of 95.4% 2σ range plotted). Two crosses identify dates at 3125 BC and 2950 BC from the author's samples cross-matched in the WRATH-9 pine chronology.
Grey zonation denotes dry phases inferred from abundance of tree-ring samples in Ireland (Turney *et al.* 2006). See Appendix I for radiocarbon data and sources.

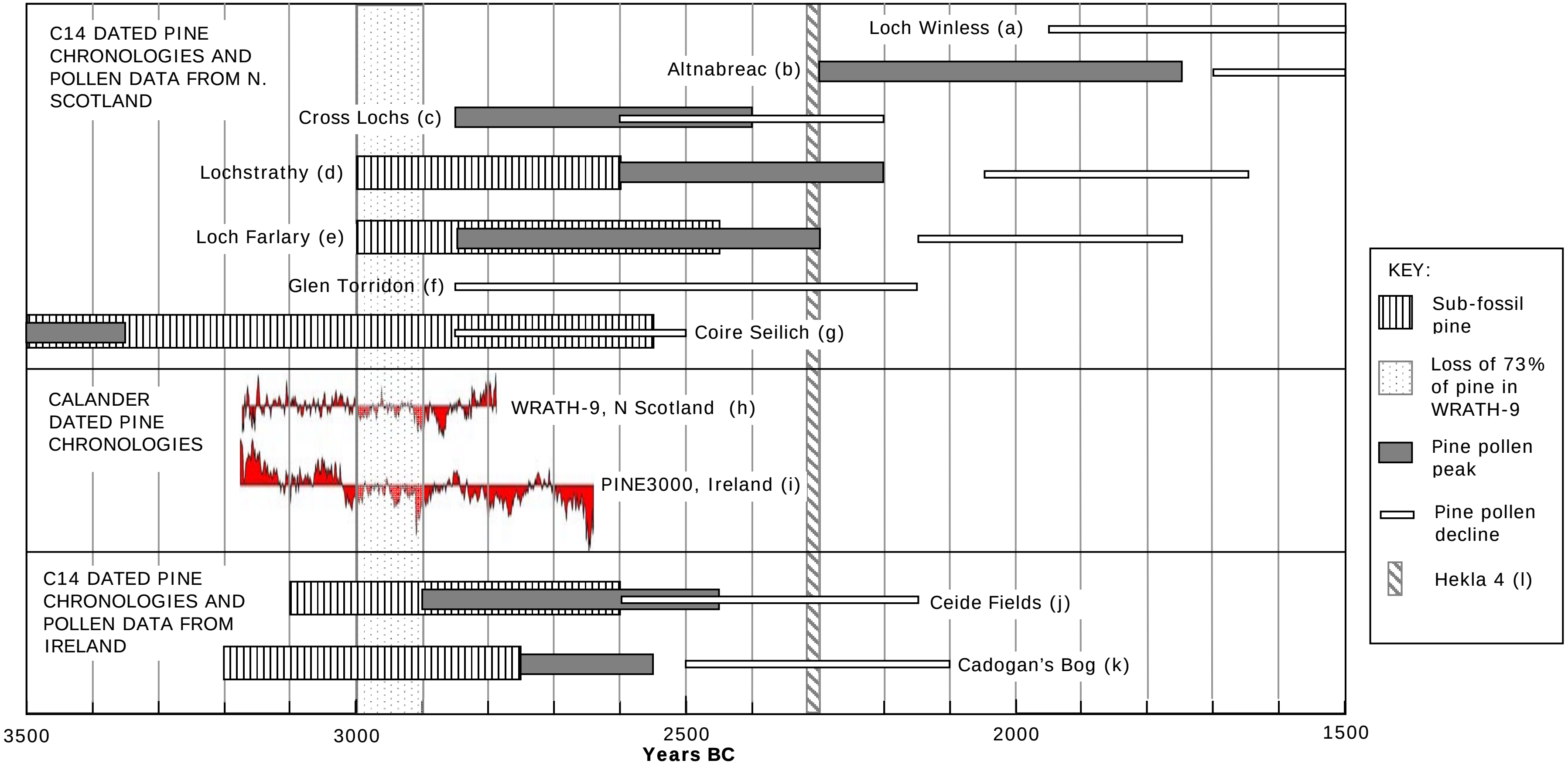

Figure 87: The temporal relationship between radiocarbon dates from sub-fossil pine and peat over the range 3500-1500 ^{14}C cal. yr BC in Scotland and Ireland Scots (95.4% 2σ range plotted, rounded to nearest 50 years).
Sources: a (Peglar 1979); b (Blackford, *et al.* 1992); c (Charman 1994); d (Gear & Huntley); e (Tipping, Ashmore, *et al.* 2007); f (Anderson 1995); g (Bridge, Haggart, *et al.* 1990); h (Author); i (D Brown, pers. comm.); j (Caulfield, O'Donnell, *et al.* 1998), k (Mighall, Lageard, et al. 2004) & (l) (Hall, Pilcher, *et al.* 1994). Note: The pollen decline uses radiocarbon dates generally located withing the 2½% tail of distrubution.

This research shows the ability of some pine to survive beyond a transition to climatic deterioration. This highlights the potential of subfossil pine to provide precise information on the timing and nature of climatic changes, but indicates the pine decline to be an imprecise target for the timing of these events. Due to the synchronicity of germination and the problem of remnant trees surviving long after the majority of mortality in a pine population, the first appearance of pine is considered to be the more precise horizon for comparison. Therefore the centre rings of Holocene subfossil pine stumps are suggested to to the more precise and informative target for radiocarbon dating.

4.3.5.3 The relationship between pine horizons in peat and climate

The climatic conditions for the occurrence of mire are quite well understood. The widespread occurrence and long accumulation of peatland suggests this has been a predominant state in Scotland since the mid Holocene (Section 1.2.1). This research contributes to our understanding of the occurrence of well preserved subfossil pine in the mires across northern Scotland. Well preserved subfossil pine surviving with bark, reinforces that a mires predominant state of low biological activity preserves pine once in the catotelm. The analysis of modern pine growing on mire in this research also supports the hypothesis that climatic conditions in Scotland today are minimal for the growth of pine on mires. The lack of synchronicity found in the germination of modern pine on the mires in this research suggests that current climate normally suppresses the widespread colonisation of mire surfaces. The evidence from this research is consistent with the occurrence of an extensive horizon of Scots pine in the mires of Scotland, coinciding with temporary shifts to dryer conditions.

This mechanism for preservation is further supported by pollen analysis, where counts have been conducted through a subfossil pine horizon. Daniell (1997) at Loch Shin identifies increases in *Calluna* (suggesting drier conditions) 20 mm below the *Pinus* pollen peak and slight increases in *Sphagnum* 20-120 mm above (indicating a return to wetter conditions). At Loch Vatchan, similar increases of *Calluna* occur 30 mm below the start of a *Pinus* pollen peak and 100mm below the peak itself, while a peak of *Sphagnum* occurs 100mm above the pine peak (Daniell 1997).

4.3.6 Disturbances

Based on work in Ireland, Bradshaw (1993) suggested that declining *Pinus sylvestris* populations in western Europe may have resulted from a reduction in fire frequencies, with fire necessary for maintaining pine dominance both through the exclusion of less fire-tolerant competitors and by creating conditions favourable for pine seedling regeneration. It has long been speculated that natural fire may have helped shape Scottish pinewood communities. Data presented give an indication of the effects of fire and mammals on Scots pine, factors of intervention which are important to establish so that the climatic response of pine can be better assessed.

4.3.6.1 Scars

Difficulties in differentiation between fire (Figure 88) and mammal scars (Figure 89) have already been discussed (section 4.2.2.2), but a further difficulty occuring in subfossil pine is made by diagenetic changes of the wood, which can make the positive identification of burnt surfaces difficult. The limited numbers of scars identified (3% of the sample) allows only very tentative interpretations to be made, but this problem is not limited to this research. Studies in England and Ireland (Lageard *et al.* 2000) also indicate low recovery rates of between 1-15%. The limited number of scars identified however should not belittle the significance of the information they can provide in respect of the germination and life cycle of pine.

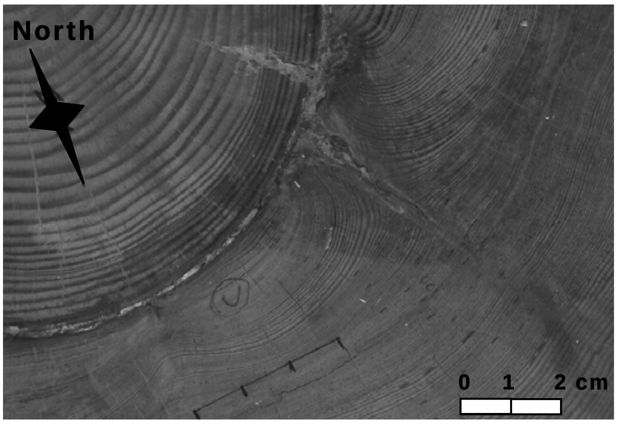

Figure 88: Fire scar in sample ASSA03. Photograph by: A. K. Moir, 2008.

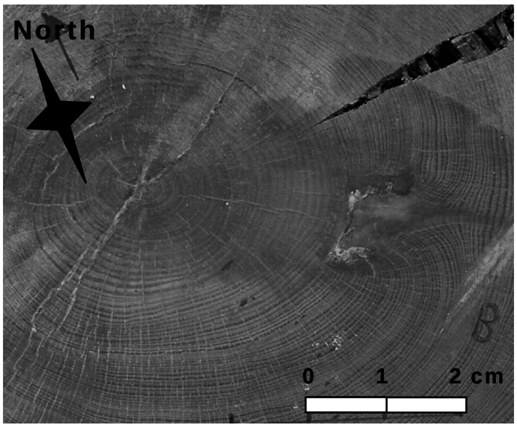

Figure 89: Mammal scar in sample POLL05. Photograph by: A. K. Moir, 2008.

Fire interpreted from microscopic charcoal evidence (Edwards *et al.* 1996, Tipping 1996) has been looked at in terms of human activity; however lightning strikes have been highlighted as important in igniting fire in the modern boreal forest in northern Europe (Zackrisson 1977, Engelmark 1984) and historic periods in northern Sweden (Engelmark 1987). Today in northern Europe 5-20% of all forest fires are ignited by lightning (Suffling 1992). Scars in sequences cross-matched in the WRATH-9 chronologies identify three probably localised fires in RY83, 100 and 133. Three fires over the length of the WRATH-9 chronology indicate an average occurrence of once every 150 years. This compares to an average interval of 170-240 years identified for Scot pine forest during the Holocene period (prior to significant human influence) identified from charcoal layers in mires in Finland (Pitkänen *et al.* 2003) and a minimum fire return period of 74 to 182 years from pine chronology dendrochronologically dated to 2881-2559 BC at White Moss, England (Lageard *et al.* 2000).

The three fires occur over a short period of 50 years and two fires are just 17 rings apart. These fires broadly coincide with a period of high radial growth (between RY90 and 110) probably indicating a lower water table. This analysis suggests the fires are related to a short period of drier climate which has a much lower minimum fire return period and supports findings by other workers that there is probably an underlying climatic control of fire frequency in Scotland (Macklin *et al.* 2000) and that Holocene pine communities in the Highlands are not fire dependent (Froyd 2006). Age-studies of forest stands have shown forest fires have commonly been followed by pulses of successful pine regeneration (Zackrisson 1980), but there is no evidence from this analysis of subfossil pine to support this. With the exception of pine from Lochstrathy {Gear 1989), few other workers on subfossil pine in Scotland identify fire scars (Bridge, Haggart, et al. 1990, Daniell 1992, Daniell 1997), although this may be due in part to altitude. Incidence of fire changes with height above sea level, stands 100-200 meters below the forest limit rarely burn, while stands further below are more strongly affected by fire (Zackrisson and Östlund 1991). Both the sites at Loch Assynt and Polla on Loch Eriboll where fire scars are identified in subfossil pine in this analysis are under 80 m altitude, while fire scars were not identified at the five other sites in the WRATH-7 chronology which are above 130m. In comparison to much of Europe, where fires add considerable uncertainty to climatic inference (Väliranta *et al.* 2007), the low incidence of fire seen on Scottish peats during the growth of Scots pine suggests their good potential for use in water level reconstructions.

The occurrence of just two mammal scars in subfossil pine at Loch Assynt, an absence of abrupt radial growth release characteristic of trees breaking though the browsing limit (Vila *et al.* 2003) and the widespread germination of subfossil pine, all indicate that grazing or damage by mammals at *c.*3150-3090 BC in northern Scotland was not a significant limiting factor to pine colonising mire. From this research it is not possible to determine, whether deer numbers in particular might have been limited by human activities. Nevertheless, mammal scars where species can be identified could be important in helping to clarify the archaeological record of mammal in Scotland. For example the introduction of the rabbit (*Oryctolagus cuniculus*) and extinctions of beaver (*Castor fiber*) and elk (*Alces alces*) both of which were characteristic of the large mammal fauna of much of the Boreal forest (McCormac and Buckland 2005).

4.3.6.2 Human activity

No direct evidence for human activity is identified through this analysis. The high percentage of exposures of subfossil pine found at the base of peat cuttings suggests that while peat removal commonly occurs, pine stumps are usually left by peat cutters. This is supported by evidence from Loch Farlary (Tipping *et al.* 2007a), which suggests that the removal of stumps of pine in peat is labour intensive and unlikely to have frequently occurred in the past.

The tentatively dating of the WRATH-9 chronology to span 3175-2790 BC places it in archaeological terms perhaps significantly at the end of the Neolithic (a traditional archaeological subdivision of cultural periods spanning about 4000-3500 ^{14}C cal. yr BC). Turney *et al.* (2006) examine radiocarbon dates from Irish archaeological context against the precise dates afforded from Irish tree-ring chronologies to demonstrate environmental change as a significantly important factor in influencing human activity in the landscape. Felling dates for the track way construction at Campmoor, Germany from 2900 to 2882 BC demonstrate a human response to a widespread shift from drier to more humid climate conditions in peat (Leuschner *et al.* 2007). Hayes (1993) summarises that between about 4000-2000 ^{14}C cal. yr BC, Neolithic track ways were laid down over deepening mires. While such track ways have yet to be identified in Scotland, a wealth of other archaeological data offers opportunities for correlation to precise tree-ring dates.

4.3.6.3 Volcanism

An increase in bog wetness was noted by Dwyer (1997) and Caseldine (1998) across a tephra isochron at 2300 ^{14}C cal. yr BC, although the tephra was never geochemically typed. Dwyer and Mitchell (1997) report two separate isochrones around 2500 ^{14}C cal. yr BC. Daniel (1997) reports unidentified tephra shards 0.23 m above the pollen peak associated with the pine horizon at Loch Shin, 0.21 m above at Vatchan and Hekla 4 tephras at 0.18m above the pine peak at Strath Dionard.

Not least because of a possible about 700 year discrepancy between the radiocarbon dates of subfossil pine and peat (section 1.2.2), the demise of subfossil pine from the north Highlands of Scotland at *c.* 3000 BC and the general pine decline identified in the region through pollen analysis at about 2000 ^{14}C cal. yr BC, could well be the same event. Blackford *et al.*'s (1992) hypothesis that the eruption of Hekla 4 caused the demise of the pine growing on peat surface cannot be resolved without greater accuracy of dating peat stratigraphy. The end of peak of pine pollen at about this time could indicate climatic deterioration brought about by the Hekla 4 eruption. However, Hekla-4 has been associated with narrow band of tree-rings in the Irish oak chronology beginning 2354 BC, which reach there narrowest in 2345 BC {Baillie 1995 BAILLIE1995B /id}. If correct these precise dates places the eruption some 650 years after the start of the pine decline identified from sub-fossil pine in the WRATH-9 chronology and some 450 years after then last pine died. While Hekla-4 seems unlikely to have resulted in the pine decline, germination conditions could be related to other layers of volcanic ash. Research into the effects of applications of phosphate fertilizers on pine, might be usefully compared to the chemical composition of modern volcanic ash layer to help assess its possible effect.

4.3.7 Further research on sub-fossil pine

4.3.7.1 Dating and extending the WRATH-9 chronology

Close examination of the first and end 50 years of component sequences of earlier reference chronologies might be considered useful to identify and resolve problems of missing rings and probably increase cross-matching. The sharing of data has proved to be an important prerequisite for successful cross-matching of pine in the past (Eronen *et al.* 2002), therefore cooperation between the workers who have developed sequences and chronologies from this period could rapidly enhance progress. Daniell (1997) has developed other subfossil pine chronology for Scotland: Fain (FAI006, 3446-3197 BC), Knockanroch (KNO001, 3442-3351 BC), Srath Dionard (SRR-5796, 4270 ± 45 calibrated to 3050-2700 ^{14}C cal. yr BC) and Laxford Bridge (SRR-5801, 3935 ± 45 calibrated to 2600-2250 ^{14}C cal. yr BC). Legeard in (Mighall *et al.* 2004) has also worked on pine likely to be from the same expansion of pine in Ireland.

Differences between cross-matching and general growth rates of the trees at the centre and edge of the site at Druim Bad a’ Ghaill provide some justification for forming separate mean chronologies. Despite the small number of samples from this site, removal of some was found to increase cross-matching with some other site mean chronologies. This idea is supported by the modern pine growing on mire at Monadh Mor where coeval samples cross-match to form two distinctly separate chronologies. The relationship between radial growth and water table is considered the most likely cause for different responses by pine in different areas of mire. Overall mean site chronologies may not always be appropriate and in some instances may reduce the climatic signal and the potential to cross-match.

Modern pine highlight the significance of individual site factors and clearly indicate not all occurrences of pine growing on mire are climatic related. Within its former latitudinal and longitudinal limits of expansion, an altitudinal expansion of pine might also be expected. A wider range of ^{14}C dates from mountain environments south of the current pine treeline (such as the Cairngorms and Rannoch Moor) suggest conditions for the growth and subsequent preservation of pine extend over a wider period. These mountainous areas could help extend chronologies and provide evidence for altitudinal changes in tree-line.

4.3.7.2 Other periods of subfossil pine preservation

Other horizons of subfossil pine present the opportunity for precise dating of inferred Mid-Holocene climate shifts from subfossil pine in the UK. Radiocarbon dating and other evidence indicate a number of broad temporal bands to target. All previous ^{14}C dates for subfossil pine in the northern Highlands of Scotland have suggested a single horizon; therefore the identification of multiple horizons of pine at some of the sites sampled in this research was unexpected (see Table 5). One and two lower horizons of subfossil pine observed at Polla and Loch an Ruathair respectively suggest earlier expansion(s) of pine may simply have been missed in work so far and indicate a potential to precisely date other periods of pine expansion. Gear (1989) tentertively suggested Badanloch (NGR: NC789331) and near Syre (NGR: NC669445) contained two layers of pine. A possible earlier advance of Scots pine northwards and onto peat is identified at Loch Shin. A filtered (Baillie and Pilcher 1973) version of the Loch Shin chronology is crossdated against the Irish - Garry Bog pine 1 chronology (Brown, 1991), with a *t*-value of 4.21 (Daniell 1997). The slightly shorter 220 year SHIN-ED chronology remains tentatively dated at 3441-3222 BC at the same relative position, but with a slightly higher *t*-value of 4.36 against the raw ring width version of the Garry Bog pine chronology. The dating of the chronology was supported by a "wiggle match" of ten ^{14}C dates, to range from 3495 +17 -40 to 3257 +17 -40 ^{14}C cal. yr BC (Daniell 1997). Re- wiggle matching of these dates using OXCAL 4.0 (Reimer *et al.* 2004) at annual resolution produces a date range of 3319-3299 ^{14}C cal. yr BC. The Loch Shin chronology suggests a possible expansion of pine into northern Scotland slightly before the *c.* 3200 BC advance identified in this research which needs further investigation. This apparent earlier horizon of pine, together with other occurrences detailed below, highlight a potential to extend the WRATH-9 chronology.

Other workers have identified multiple horizons on pine at exposures further south. Some of these earlier periods of pine expansion and subsequent preservation have been ^{14}C dated and suggest the broad timing of other possible expansions of pine which might have the potential to be precisely dated through dendrochronological analysis:

In Scotland: 5250-4650 ^{14}C cal. yr BC at Clashgour A (Bridge *et al.* 1990)
5000-4700 ^{14}C cal. yr BC at Loch Glascarnoch (Daniell 1997)

In England: 6400-6050 ^{14}C cal. yr BC at Over Wood Moss (Tallis and Switsur 1983)

In Ireland[3]: 6600-6100 ^{14}C cal. yr BC at North Mayo (Caulfield *et al.* 1998).
5800-5450 ^{14}C cal. yr BC at North Mayo (Caulfield *et al.* 1998).
5650-5200 ^{14}C cal. yr BC at Cadogan's Bog (Mighall *et al.* 2004)

Turney *et al.* (2006) infer the timing of dry periods, a basis of abundance of tree-ring samples in Ireland (see Figure 86). Whereas the broad timing of climatic deterioration is indicated by a wide range of other analyses. Bridge *et al.* (1990) then inferred that periods of high pine pollen frequencies might be correlated with drier climatic phases. Bridge *et al.* (1990) also proposed a correlation between the abundance of radiocarbon-dated subfossil pine in Scotland and wetter climatic phases suggested by deuterium/hydrogen (D/H) ratios measured from pine tree-rings (Dubois and Ferguson 1985). D/H ratios within tree-rings are thought by Dubois and Ferguson (1985) to be determined by precipitation levels. From the patterns derived from 3 radiocarbon-dated data-points, they have inferred a series of three 'pluvial' episodes in the early and mid-Holocene: before *c.* 5550 BC, at 4300-3850 BC and before 1350 BC (although the first and third 'pluvials' are poorly defined through the scarcity of available macrofossils). The 'pluvial' episodes of Dubois & Ferguson (1985) have yet to be demonstrated by independent means, and there are possible uncertainties in their sampling strategy (Pears 1988), replication of results and causal mechanisms in inducing changes in D/H ratios; other applications of D/H measurements, though on peat, have assumed a relationship with temperature, not precipitation (Dupont 1985, Van Geel and Mook 1989). Nevertheless, this work draws the observation that the Holocene was characterized by significant climatic fluctuations, intense or prolonged enough to disrupt the natural vegetation cover.

Multiple transitions between wet and dry periods in northern Scotland are also indicated from other evidence: peat stratigraphy (Aaby 1976, Barber 1982, Tallis and Switsur 1983), lake-levels (Magny 1992, Harrison and Digerfeldt 1993, Yu and Harrison 1995) and humification analysis (Binney 1997, Anderson *et al.* 1998). A state of equilibrium,

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[3] Identify lower second horizons of pine.

whereby the widespread colonisation of mires by Scots pine at their northern limit in Scotland is predominantly suppressed by the climatic conditions of the mid to late Holocene is supported by this research. If multiple layers of subfossil pine in northern Scotland are found to be widespread they may elucidate earlier episodes of change in the northern limit of Scots pine. Most of these investigations identify another widely synchronous (about 2000-1500 ^{14}C cal. yr BC) shift to a drier period in northern Scotland.

The occurrence of a horizon of subfossil pine indicates a period when conditions became relatively wetter. The presence of subfossil pine on peat probably corresponds with periods of dryer conditions and therefore it is unlikely that the rate of peat accumulation on mires is constant. Binney (1997) highlights wind as a factor controlling the surface conditions of mires, a factor critical for both the colonisation and preservation of Scots pine in northern Scotland. Transitions between different accumulation rates may be triggered by changes in humidity (Hughes and Barber 2004). Tallis (1983) identifies broadly consistent periods of low and high peat accumulation (Lower 7000-6300 ^{14}C cal. yr BC, high at 5000-4500 ^{14}C cal. yr BC, lower 3800-3300 ^{14}C cal. yr BC and high by 2000 ^{14}C cal. yr BC). A multi-proxy approach of pollen analysis and humification analysis at sites with layers of pine is required to establish whether continuous conditions of preservation exist between each layer of pine. Such research might also be usefully combined with palaeowind studies on aeolian sediment influx in peat (Bjorck 2004), to extend our understanding of past regional storm climate and their influence on peatland.

4.4 Dendroaeology

The term dendroaeology (from the Latin word aeolo, meaning air or wind) is used here to define the science that uses tree-rings to study past and present wind. Wind is considered the principal agent in the disturbance of Scottish forests at present (Miller 1985, Quine 2003), yet previously has rarely been considered in dendroclimatic analysis. This research hypothesised that asymmetrical radial growth found in Scots pine in the north of Scotland might be used as an indicator of the direction and possibly strength of the prevailing wind. Despite the small number of samples, asymmetric growth shown in modern Scots pine appears to have a consistent relationship with the current W/S.W. prevailing wind (Figure 90). The mean orientation of maximum radial growth at eleven modern sites is found to coincide well with the UK's current W/SW prevailing wind. The mean difference between the maximum and minimum radii from these sites is -24%. Seven of these sites are located on peat where there is little influence from aspect or slope. The results of this research suggest that mean maximum radial growth in Scots pines occurs in the lee of the prevailing wind. These findings are in accordance with two other studies on conifers (Bannan and Bindra 1970, Hamilton 2002). Windthrow evident at four of the modern sites analysis (Achanalt, Borgie Forest, Eilean Sùbhainn C and Strathnaver C) is also found to coincide with the direction of mean maximum radial growth. Although it should be recognised that windthrow is the result of a short term wind event and therefore not necessarily related to the long term influence of prevailing wind. The coincidence of windthrow with maximum radial growth does suggest a tree growth adaptation to strong winds from the W/SW.

Variation between three sites on the island of Eilann Sùbhainn in Loch Maree, demonstrates that surrounding topography and the funnelling of the wind is likely to influence exposure and asymmetrical radial growth in trees in response to wind over short distances. Loch Maree is approximately 19 km long and lies on a NW/SE orientation. Site C at Eilean Sùbhainn is located on mineral substrate on the west shore and the most exposed of the 3 sites sampled on this island. The orientation of mean maximum radial growth infers a prevailing wind from a WSW direction. One sample shows a 46%

difference between the east and west core, this sample could not be cross-matched possibly due to strong winds causing missing rings. The direction of mean maximum radial growth also corresponds with the direction of the four windthrown trees observed at this loch edge site. Five trees windthrown by a south-west wind and one by a westerly wind were recorded at Strathnaver A. The mean orientation of maximum radial growth at sites A and C both occur to the NNE inferring a SSW prevailing wind, which is in close agreement with the evidence of the windthrown trees in the area. The mean maximum direction of radial growth at Borgie and Strathnaver is useful to help indicate that trees in the far north are similarly affected by prevailing winds.

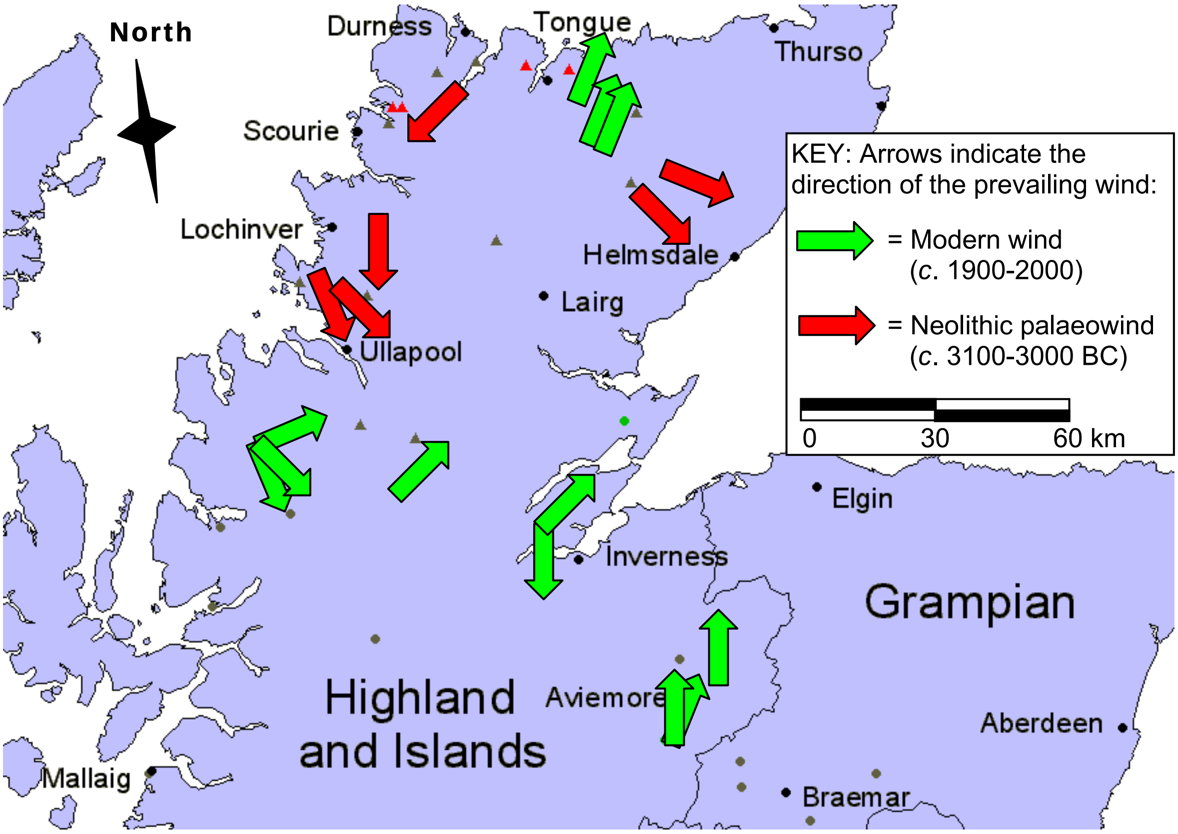


Figure 90: Prevailing wind and palaeowind interpreted from the direction of minimum radial growth in Scots pine at 12 Modern and 6 Neolithic sites in northern Scotland.
See Figure 24 for key to other symbols.

Surprisingly, the eight trees sampled from site B at Strathnaver (which was considered the most exposed, being at the western edge of the forest and bordering onto the river valley) produced only 3 samples with differences between the maximum and minimum radii greater than 10% and these were all orientated in different directions. Site B at Strathnaver consisted of trees along the edge of the forest and this could suggest that the asymmetrical growth of trees may have been affected by another factor, such as the light, slope and aspect. Similar direction of maximum radial growth from adjacent peat and mineral substrate sites at Strathnaver do suggest that pine trees growing on both substrates in the area are affected by wind in the same way. However, sites A and B at Eilean Sùbhainn are located on bog, (although site B may be influenced by slope); indicate the influence of a NW wind, rather than a SW influence identified from the mineral substrate site C nearby.

Six Modern pine sites which were sampled by north and south orientated cores produced ambiguous results that could not be interpreted. This is thought probably due to problems in sampling, where just two opposing cores were taken that were not orientated with the prevailing wind direction. A second chronology developed at Monadh Mor indicates a north prevailing wind, which is unexplained, but interestingly this chronology failed to cross-match against others in Scotland, perhaps indicating that wind can play a significant factor in cross-matching.

4.4.1 Palaeowind direction during the Neolithic

Assuming a similar response between the orientation of mean maximum radial growth in both Modern and Holocene pine to wind, the growth of pine at six coeval Neolithic sites consistently indicate a broadly northerly prevailing wind (direction ranging from a NE to NW). These subfossil pine samples are tentatively dated to between *c.* 3100-3000 BC and suggest an apparent reversal of prevailing wind at that time, which is surprising and highlights an area for further investigation. However, Pearsall (1956) highlights a strong north-westerly component in modern meteorological wind data for Wick and suggested very strong wind and rain influence from the sea to the north or north-west affected bogs and the movement of sand dunes. A possible change in prevailing wind at this timing could be related to southward incursion of the polar front in the eastern N. Atlantic *c.* 4000 ^{14}C cal. yr BC (Bond *et al.* 1997).

A possible relationship between roots and wind could also be analysed in the Neolithic subfossil pine due to the samples predominantly being taken from stumps where roots are sometimes visible. Roots are also known to reflect a trees physiological response to wind stress (Nicoll and Ray 1996). Nicoll and Ray, use Sitka spruce (*Picea sitchensis*) with shallow root systems restricted by water table to identify three adaptive growth responses to wind movement:

- Shallow rooting with more structural root mass on the leeward side of the tree relative to prevailing wind direction.

- The buttressed parts of roots had greater lateral and vertical secondary thickening above rather than below the biological centre producing a T-beam cross-section.

- Roots tended to develop I-beam and oval cross-sections, particularly on the leeward side of the tree, once 0.5 m from the centre of the tree.

These three responses are considered to improve resistance to vertical flexing, increase the rigidity of the soil-root plate and so help counteract tree vulnerability to windthrow. The orientations of the maximum radial growth and the largest root appear to coincide at Druim Bad a' Ghaill and possible Loch Ruathair, which is the expected physiological response for roots to the interpreted direction of wind stress (Nicoll and Ray 1996). However, at Loch Assynt and Strath Kanaird orientation of maximum radial growth and largest roots appear to oppose, which suggest that the largest root grew not on the lee side, but on the side exposed to the prevailing wind.

The two uncross-matched chronologies developed at Druim Bad a'Ghaill both show coinciding orientations of maximum radial growth and largest root and indicate the WSW to be the direction of prevailing wind. However, the failure to dendrochronologically cross-match these two chronologies with the WRATH-9 chronology suggests that they may not be coeval. Previous combined dendrochronological and C^{14} dated studies provide a number of examples where subfossil pine of quite different age can occur in what visually may appear a single horizon at a site, e.g. Clashgour A (Bridge *et al.* 1990); Loch Glascarnoch (Daniell 1997) and Loch Farlary (Tipping *et al.* 2007a). Thus, the results of these undated chronologies are not considered to contradict the direction of prevailing wind which is otherwise found to be remarkably consistent from the orientation of maximum radial growth at the six sites of Neolithic pine.

There is little other contemporary evidence on wind directions against which to compare. Tipping (2007) found the mean root orientation from 42 sub-fossil pine probably dating from about 5250-4650 ^{14}C cal. yr BC at Clashgour on Rannoch Moor to be towards the SW. Tipping, references Nicoll and Ray (1996) to infer the trees are adapted to wind stress broadly from the west. However, as previously stated, Nicoll and Ray (1996) state that adaptive growth response of shallow tree roots to wind stress is more structural root mass on the leeward side of a tree relative to prevailing wind direction, and this is supported by Mergen (1984). This infers that the prevailing wind at the Clashgour site was broadly from the north east. The Clashgour A site is located on an extensive flat area of peat; 1 km west of the NE/SW aligned Loch Tulla. The valleys of the Scottish Highlands tend to very effectively funnel the wind (Roy 1997). Therefore given the sites location the orientation of roots may not be inconsistent with a broadly northern prevailing wind during this period of pine expansion onto bog. Direction of fall in Tipping (2007) also measured direction of fall in 40 trunks and found the mean direction of fall to be to the east, although four trunks were also found windthrown to the west. Interestingly, a study in southwest Britain by Allen (1992) finds subfossil trees felled by winds ranging from NNW to SSE. Unfortunately, though the trees are rooted in peats dated over a wide range (from 6000 to 2500 uncalibrated ^{14}C yr BP.) it is not possible to establish whether changes in wind direction occurred with time.

The changes in the direction of maximum radial growth over short distances at Eilean Sùbhainn suggest the effects of topography are likely to influence asymmetrical radial growth and probably root development. While most of the Neolithic sites of pine would be quite exposed to the influence of a prevailing wind from a northerly direction, the site at Loch Assynt is tucked just to the south, in the lee of Quinag (a 2650 m high mountain). It is likely that the mountain would influence northerly airflow and possible that the root direction of trees at Loch Assynt could be a response to an area of slack air (Figure 91). The relationship between root orientation and wind from these results currently remains uncertain.

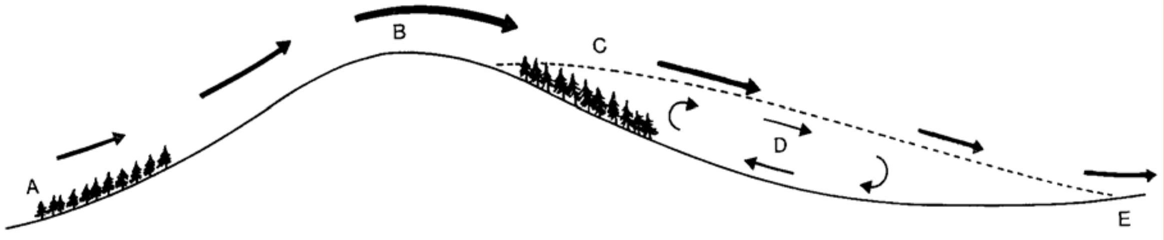


Figure 91: Features of the airflow over forested hills. Source: (Quine *et al.* 1995).
A: presence of forest on lower slopes reduces wind speed at top; B: speed-up of wind at summit; C: separation of flow in lee of hill encouraged by presence of trees; D: slack air in lee of hill; E: re-joining of air flow.

4.4.2 Physiology responses of Scots pine to wind

A reasonable understanding of mechanisms for the cause of asymmetrical growth in pine is considered fundamental before invoking tree-ring data as a proxy for prevailing wind. One physiological mechanism which could account for the relationship is discussed in section 4.1.2, whereby harsh winter gales may lead to loss and damage of a tree's needles/branches/trunk and thereby reduce its photosynthetic potential and so its radial growth increment the following summer. This is conjectured as a mechanism by which the radial growth of a tree on the side facing the wind might be reduced. Conversely though, a second response of trees under stress from wind is a thickening of growth rings in the lower stem close to the base (Wilson 1975). This could lead to increased radial growth of a tree on the side in the lee of the wind. The total effect of wind-induced flexure stress on tree growth is the development of a more compact growth form, with greater stem taper, shorter branches and smaller leaves (Telewski 1995). At tissue level, asymmetrical radial growth in coniferous species usually results from an increase in the number of tracheids in the direction of flexure on the leeward side of the stem (Bannan and Bindra 1970, Burton and Smith 1972, Telewski and Jaffe 1981). The tracheids that develop in this region are shorter than tracheids in other portions of the stem (Bannan and Bindra 1970).

Other factors being equal, the mean difference between the maximum and minimum radii in pine from the Holocene sites of 41%, compared to 24% from the Modern sites, might be taken to suggest a stronger influence (or speed) of wind on radial growth during the Holocene. However, it would be unwise to infer this because of a difference between the mean sampling height between Modern and Holocene pine, sampled at 0.35 and 0.07 m respectively. Though this mechanism may help explain the asymmetrical radial growth of pine, it is less likely to explain the relationship between radial growth and February NAO which is shown by moving correlation functions. Further research is needed to establish if thickening of growth rings in the lower stem is a significant physiology response of Scots pine to prevailing wind direction and wind.

4.4.3 The influence of NAO on climate and pine growth

To observe the effect of a change in climate it is important to identify what factors are likely to change and whether these variations are likely to be observable. Change in North Atlantic circulation alters the extent of oceanicity, causing variation in temperature, precipitation and NAO indices over time. The climate between the two periods (1881-1930 and 1831-1980) changes considerably (section 3.4.7), NAO indices in February show the largest percentage change of the climatic variables (a decrease of 84%), July/August temperatures show a mean 0.5°C increase, January/February temperatures change little but possibly show slight decrease. Together the evidence is consistent with stronger westerly winds between 1881 and 1930 bringing milder winters, while weaker westerlies (or even easterly winds) between 1931 and 1980 lead to colder winters. An expected reduction of winter temperature in the latter period may be masked by a global temperature increase, between 1914 and 2004 overall temperature has increased by 0.37°C (Barnett *et al.* 2006).

4.4.3.1 Moving correlation functions from mineral substrate pine

Over the 80 year period between 1881-1960 which was selected for correlation function analysis, the SE area chronologies growing on mineral substrate show that January and February are the most important determinant of rings' width (section 3.4.2), closely followed by July and August temperature, particularly at sites over 550 m altitude. These positive relationships are less clear in the six sites in the NW area which are generally lower altitude (ranging from 12-300 m). Nevertheless the same January/February temperature relationship with ring width is seen in three chronologies from Loch Maree, Shieldaig and Beinn Eighe. However, NAO indices in February have a stronger and more consistent relationship with tree-ring growth in the NW.

A number of authors have highlighted fluctuations in the strength of NAO and storminess over the last two centuries (see section 2.3.5). Moving correlation functions are a useful method to examine for changes in the relationships between NAO and ring width. Moving correlation functions show that chronologies in the SE area which extend before the 1920s lose their positive correlation with January and February temperature and NAO in

February from this time. Chronologies from the NW area also show reductions and sometimes a loss of these positive correlations with temperature and NAO in the same months, occurring from the 1920s (Figure 92).

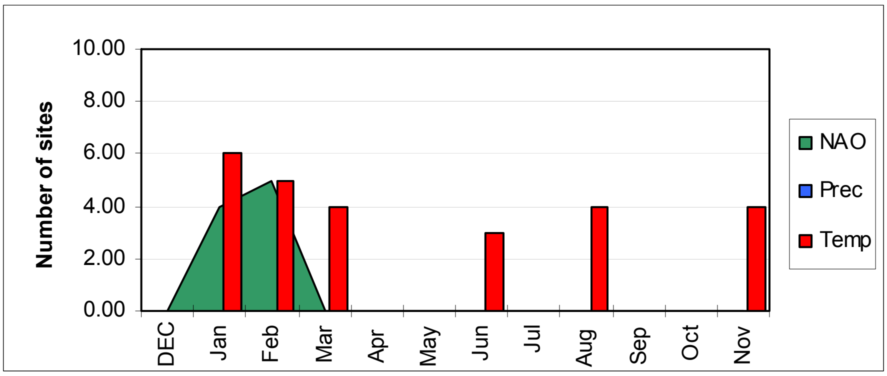


Figure 92: Number of mineral substrate sites of Scots pine sites out of 10 in northern Scotland that moving correlation functions show have a loss or decrease in monthly climate relationship from the 1920s. Only totals ≥ 3 shown for clarity.

Moving correlation functions show a clear change in the relationship between climate and the ring width of pine occurs in the 1920s in Northern Scotland. This is clearest at SE sites between 280-400 m and noticeable absent from sites above this height. It is also evident at three sites in the NW between 100-300 m. This suggests that an increase in temperature has caused temperature to no longer be such a limiting factor on the growth of pine at these sites.

4.4.3.2 Moving correlation functions from bog pine

In the NW area, the two chronologies from the down slope margin at Eilean Sùbhainn show a gradual downturn in growth from the 1940s and three trees become too narrow to be reliably measured in the 1970s altogether. Pine from the crown of the bog show a downturn of growth from the 1950s and radial growth of three trees in the 1970s and three trees around 2000 become to narrow to be reliably measured. North Scotland has become 21% wetter between 1961 and 2004 (Barnett *et al.* 2006), therefore one would expect a reduction in the growth of pine on mire and little recruitment over this period. Decadal growth rates of just 0.25 and 0.30 mm yr^{-1} in 2000 suggest that pine growth is currently marginal. This is in accord with prolonged periods of high precipitation raising the water table in peat and hence inhibiting pine growth as tree growth (Boggie 1972, Mannerkoski 1991). However, correlation functions identify the positive influence of October temperature on radial growth from the 1920s which is consistent with pine in the NW area taking advantage of an extended growing season. Barnett *et al.* (2006) identify a 1°C increase in temperature, which is likely to lengthen the growing season and increase the annual radial growth of pine.

In the SE area at Abernethy, sites A and B bog pine show a general reduction in radial growth from around 0.75 mm in the 1880s to under 0.50 mm in the 1920s, then a gradual recovery to 1.00 mm in the 1970s. Interestingly, although overall North Scotland has become wetter Braemar shows a 17% decrease in rainfall when comparing the periods 1881-1930 and 1931-1980. The recent increased growth of pine at Abernethy is possibly a response to a localised reduction in rainfall. Site C however, shows a gradual reduction in radial growth from 0.75 mm yr^{-1} between 1910-1940, to 0.50 mm yr^{-1} in the 1980s (Figure 141). Although, the growth of pine at all the Abernethy sites show a reduction in radial growth in the 1920s which may be in part a response to fire.

This analysis indicates that with the climatic conditions in Scotland today the growth of bog pine is minimal, and provides evidence that radial growth has a negative relationship with water table and positive relationship with temperature. This suggests that the growth of bog pine is likely to be affected in two conflicting ways by climate change in Scotland. Peat substrate sites at Abernethy show NAO indices in May as the most important determinant of ring width. This negative response becomes significant from the 1910s, suggesting strong westerlies have an adverse influence on ring-width, but the mechanism for a response in this month is not understood. Jones and Lister (2004) show that while NAO has its strongest influence in the winter season (prior December to February) it was also just significant in the spring season (March to May).

4.4.3.3 Correlation of chronologies and climate data for 1881-1930 and 1931-1980

Simple correlation of the BOREAL-PN and OCEANIC-PN chronologies between 1881 and 1930 (Table 20) confirms the results of moving correlation function analysis that the majority of Scots pine in the SE area show a strong positive relationship between radial growth and temperature in January, February, July and August and these relationships are often absent from pine in the NW area (Figure 81 and Figure 82). However, neither mineral substrate chronologies for the SE or the NW area show a significant relationship with NAO indices. However, February NAO over this period correlates well with February temperature, and February temperature does correlate with the BORAL-PN chronology. For the period 1831 to 1980 however, the chronologies in the NW area show positive correlations with February, July and August temperature, while with the exception of February temperature, these relationships are lost in the chronology from the SE area (Figure 92 and Appendix XI). This correlation analysis also demonstrates that during this period the NW area chronology develops a significant relationship with NAO indices.

4.4.3.4 Evidence from pointer years

The absence of narrow pointer years between 1910 and 1939 coincides with a period of weak NAO indices between 1900 and 1940 (Jones *et al.* 2003) and might appear to reinforce a close relationship between the radial growth of pine and wind. However, this period would be expected to lead to colder winters causing more narrow rings rather than the absence identified. In recent years it has been argued that the NAO to a large extent controls the behaviour of westerly winds across the Atlantic Ocean (Dawson *et al.* 2002). Positive values of the NAO index correspond to low pressures over Iceland and are associated with stronger than average westerly winds over the North Atlantic (producing warmer winters), negative values correspond to high pressures over Iceland and weakening of westerly winds (producing cooler winters). Since the 1980s, the NAO has been highly positive which had been assumed related to an increase in wintertime storminess and mean wind speeds in the North Atlantic region (Günther *et al.* 1998). Dawson *et al.* (2002) however, highlight that the period of exceptional storminess between the 1870s and 1900s does not coincide with a strongly positive NAO index and argues that during this period the North Atlantic storm track may have been displaced further south, by an expansion of the Greenland anticyclone.

Pointer years allow the influence of NAO on the growth of Scots pine to be further examined, by comparing specific years to weather records (www.metoffice.gov.uk):

- 1947 saw the lowest February NAO (-4.6) in the period analysed, caused by an anticyclone becoming anchored over Scandinavia which then blocked the eastward progress of Atlantic depressions, forcing them to take routes south of the UK. This resulted in easterly winds causing the coldest February on record in many places and unusually heavy snow fall over much of England and Wales. Conversely, western Scotland experienced unusually dry and sunny conditions. Interestingly, a narrow pointer year is identified in Scots pine from the SE area, but not the NW.

- 1963 saw anticyclones to the north and east of the British Isles (although at one point high pressure extended from the southern Baltic to Cornwall) bringing bitterly cold winds from the east, deflecting depressions tracks southward, and resulting in the coldest winter over Scotland since 1879. Unlike the winter of 1947, however, most areas were sunnier than average and the winter ended early with an exceptionally mild March. The NAO indices for February only show a value of -1.9 which is not exceptionally low and this year is not identified as a pointer year for pine in either the SE or NW areas.

- 1949 and 1961 both have unusually high February NAO index values (over 4.0) indicating strong westerly winds, and leading to extremely mild winters in both years. Nevertheless a positive pointer occurs in 1949 and a negative one in 1961.

There are clear implications that increased wind, temperature and precipitation from more frequent winter cyclones may not necessarily coincide with periods when the winter NAO index was strongly positive. Interestingly, in respect of the southern displacement of depression tracks, moving correlation functions for Dimmie which is the most southerly site is the only one to show a response between ring width and both temperature and NAO indices, these relationships develop in February and March from the 1910s.

4.4.3.5 Regional relationships

Observed decreases in NAO, January/February temperature and August rainfall (at Braemar) comparing the periods 1881-1930 and 1931-1980 (section 3.4.7) are all consistent with a relaxation in the westerly winds and consequently less oceanic influence leading to colder and drier winters. Over the same period a rise of 0.5°C and 0.6°C, respectively, in July and August in the SMT data occurs. Although an interpreted overall relaxation of westerly wind is not in agreement with Jones *et al.* (2003) who shows that NAO is noticeably weaker between 1900 and 1940, it is more in agreement with the frequency of westerly days (based on Lamb Classification) which was low from the 1950s until late 1980s (Kelly *et al.* 1997). From the 1980s NAO has increased again leading to more westerlies and most noticeable in areas of the west Highlands and Hebrides, with a doubling of winter precipitation since 1961. Between 1961 and 2004 average winter pressures have been falling in northern Scotland but with little change in southern Scotland (Barnett *et al.* 2006). North Scotland is mainly an area of low pressure (the so-called "Icelandic low"). The changes suggest that low pressures are becoming lower and that the average winter pressure gradient across Scotland has increased. This should lead to the NAO index becoming mainly positive, resulting in stronger westerly prevailing winds and milder, wetter winters. However, the UKCIP02 report (Hulme *et al.* 2002) suggests a possible shift southwards of the storm tracks' current position, which may result in stronger winds across southern England, but have little change in Scotland.

The positive correlation of ring width with January and February NAO Indices in the NW area identified in this analysis, indicate NAO to be as significant a factor on pine growth at the western margin of Scots pine as temperature. Winter NAO varies in time and is known to exert a strong influence on European temperatures (Jones *et al.* 1997). In this analysis positive correlations between ring-width and temperature in January and February, closely reflect those of NAO in the same months. This suggests that the influence of NAO on pine growth could primarily be one of temperature. In Fennoscandia (Linderholm, Solberg, *et* *al.* 2003) found pine growth to have a weaker relationship with the NAO than temperature and precipitation. Linderholm, identifies winter NAO to be an adequate measure for climatic variations important for radial growth, but found Scots pine displayed reduced sensitivity with climate in the west, while the opposite was found in the east, during the second half of the twentieth century. The difference in response was attributed to the increasing temperatures and precipitation of the period. The strong relationship between ring width and NAO identified in this study is likely to be a result of the closer proximities of the sites to the ocean.

It might be expected that the radial growth of Scots pine in regional chronologies would respond to the changes in climate observed between the periods 1881-1930 and 1931-1980. Mean chronologies for both mineral and peat substrate pine in the mean NW area show a reduction in radial growth respectively from the mid 1910s and the early 1920s (Figure 93), however no clear common response to climatic change in Scotland is identified from this data.

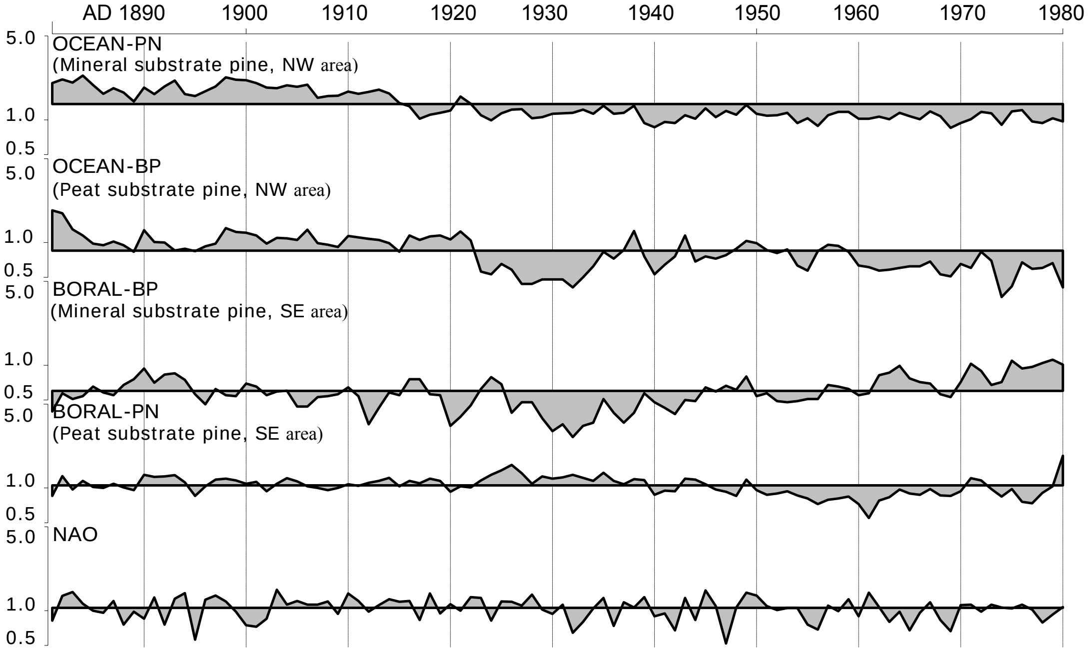


Figure 93: Plots of the North Atlantic Oscillation Indices (NAO) together with the mean pine chronologies developed for NW and SE areas of northern Scotland.
Ring width (mm) is plotted on a logarithmic scale on the y axis. To allow comparisons with tree-ring plots, ten was added to the NAO indices (Hurrell 1995) to make them positive and then these values were multiplied by ten.

A number of problems currently limit the analysis of the relationships between pine growth and climate. Limits in the length of climate data but particularly chronologies, led to differences in the periods examined by simple correlation and correlation function analysis. Most mineral substrate pine reference chronologies end in the 1970s and more chronologies extending over the length of existing climate records would be useful to examine the effects of changing climate on pine growth. The results of moving correlation function analysis clearly showed that correlation/response function analysis can be highly dependent upon the metrological time period applied, reinforcing the conclusions of Lührte (1991). In this respect the moving correlation function analysis used in this research is a significant advance over previous methods, which enables the stability of response over comparable sequential periods of time to be assessed. However, it should be recognised that by the use of the 80 year correlation window, shorter term shifts in NAO may be overlooked. Prior to the twentieth century the various existing NAO index reconstructions show an inconsistent picture for interannual and decadal scale variability (Schmutz *et al.* 2000).

Another problem is likely to be the reliability of the NAO Indices themselves. Schmutz *et al.* (2000) suggest the most reliable reconstruction is the one by Luterbacher *et al.* (1999), which extends back to 1675. Despite these problems this analysis suggests the possible use of long pine tree-ring records in Scotland could be useful to help validate or refine such NAO proxy reconstructions.

Crawford (2000) highlights warmer winters in maritime environments can have negative aspects for many species through: soil saturation, leaching of soils, soaking of germinating seeds and depression of tree lines by increasing cloud cover and high lapse rates.

4.4.4 Aspects for further research

The inter-relationship of factors of temperature, rainfall, sunshine and wind, together with the effect of the preceding year and influence of climate change on radial growth of Scots pine are not yet fully understood.

4.4.4.1 Wind and Storm frequency

Establishing Scots pine in Scotland as a proxy for wind might be considered useful to compare the influence of NAO on its growth.

This provides additional evidence for the observations of Carlisle and Brown (1968) that wind exposure is an important limiting factor as pine growth nears its northern limits in Scotland. It is also consistent with the altitudinal vegetation zone boundaries decreasing towards the northwest and north of Scotland, due to the decreasing mean July and January temperatures northwards and increasing wind speed and oceanicity westwards. This is seen in the potential tree line which lowers from above 793 m in parts of the Cairngorms to about 520 m in the northwest Highlands (Birks 1988). Pears (1967) assessed the relative factors which might limit the growth of Scots pine at high altitude in the Cairngorms and concluded that strong wind exposure alone would probably be sufficient to prevent any natural re-advance of the forest.

Walker (1984) argues that mid-Holocene vegetation change on St. Kilda, in the Outer Hebrides, was strongly influenced by increased storminess. Attempts to extend the record of storminess beyond the instrumental record to 1400 years ago have been based on detailed measurements of sea salt (Na+) concentrations in the GISP2 Greenland ice core (Meeker and Mayewski 2002). Diatom records over the last 5000 years are used by Witak *et al.* (2005) to suggest increases in cyclonic activity and climate instability in the N Atlantic to be related to a more southerly Polar Front at 2800, 2300 and 1300 ^{14}C cal. yr BC. In Orkney, the abandonment of Skara Brae has been suggested to result from sand inundation, which is dated by the radiocarbon dating on animal bones (Birm 433, 3830 ±110) to 2600-1950 ^{14}C cal. yr BC. On the north coast of Ireland Wilson *el al.* (2004) find episodes of climatic deterioration are marked by widespread dune instability. Phases of dune movement occur 4950-3550, 2650-2450 and 2050-1850 ^{14}C cal. yr BC, while 3450-2650 ^{14}C cal. yr BC may represent a period of dune net erosion (Wilson *et al.* 2004). Analysis on an extensive layer of silt across blanket peat at Achill Island in western Ireland reveals evidence for an extreme climatic event, probably a series of storms at about 3300-3200 ^{14}C cal. yr BC (Caseldine *et al.* 2005).

Most phases of aeolian activity have been correlated with cold periods in northwest Europe, also suggesting a link between winter storminess in southern Scandinavia and expansion of the polar vortex. Reconstructions of storminess based on aeolian input into a raised bog in southern Sweden (Björck and Clemmensen 2004) record peaks of storminess at 3750-3500, 3250-3150, 2950, 2650, 2250-2150 and 1725 ^{14}C cal. yr BC. Similar work in southwest Sweden (de Jong *et al.* 2006) identifies increased winter storm frequency at 2900, 2300 and 900-300 ^{14}C cal. yr BC. In Denmark, Murray and Clemmensen (2001) identify one of the main periods of Aeolian sand movement starts about 2300 ^{14}C cal. yr BC.

4.4.4.2 Wind direction

While NAO indices are considered a proxy for wind, questions have been raised over the strength of its relationship with wind and this may weaken its correlation with the radial growth of Scots pine. However, it should also be recognized that the methods advocated in this research using the direction of maximum radial growth is only an indication of a broad single direction of wind. Other wind directions might be equally active at different times of year, but which have less influence on ring width growth in pine. Nevertheless, factors being equal, it is possible that the degree of skew in the asymmetric radial growth of trees will be proportional to the wind speed, thereby providing a proxy indicator of both prevailing wind direction and speed.

Many other factors (season, substrate, topography, light, sampling height and neighbouring trees) may influence the skew of radial growth in pine whose effects have yet to be explored. It is unknown whether the response of tree growth to climatic factors might be amplified in the radii facing or in the lee of the predominant direction of wind effect. Another factor by which wind is likely to affect the growth of pine is cloud cover by effecting rates of Photosynthesis. From the mid-twentieth century, cloud cover has increased across the Northern hemisphere. Within Scotland this has been mostly marked along the west coast, where the mean daily hours of bright sunshine between 1941-1970 and 1964-1993 decreased by 16% (Harrison 1997). There has also been little discussion on modern tree selection or site factors and it has been standard practice by both dendrochronologists and forestry studies (Fourt *et al.* 1995) to select healthy dominant trees. These factors are all highlighted for further research. Greater light availability is also suggested to prevent wind direction from being identified in the growth of trees on the edge of the forest at Strathnaver. Static winch tests carried out on Maritime pine (*Pinus pinaster* Ait.) found edge of forest trees to be 20% more resistant to overturning than inner trees, with soil-root plates two times larger on the windward side (Cucchi *et al.* 2004); this also points to an influence of location on asymmetrical radial growth. Nevertheless, there appears to be significant possible applications for the future in palaeoclimate research. Advances in genetics and phylogeography e.g. (Cheddadi *et al.* 2006), are other areas of research that may also help combine our understanding of Modern and Holocene pine.

It should also be recognised that the prevailing wind and its influence on tree-growth may alter over the lifespan of the tree. Due to latter growth in stumps being affected by root buttressing; only the first 100 years of growth in subfossil pine was examined. Analysis of trunks might allow analysis to establish whether the pattern of response changes over time. The several thousand year long bristlecone pine chronologies in California could be invaluable in helping to examine the longer term influence of prevailing wind on asymmetrical tree growth.

Analysis on additional stands of modern pine in Scotland is strongly recommended to reinforce and refine the methods and results from this research. In this regard increment cores previously collected for ring counts (Edwards and Mason 2006) might provide useful additional material for Scotland at: Glenmore, Black Wood of Rannoch, Glen Garry and

Glen Affric at altitudes of 320-350 m, 250 m, 180-200 m and 320-350 m, respectively. Extending mineral substrate chronologies in both the NE and SE areas from the 1980s to present day would allow another 30 years period against which pine growth in response to metrological data could be compared.

To help isolate the climatic response of Scots pine growing on mineral substrate in the NW, it would be useful to establish chronologies from sites over 300 m. Steven (1959) indicates possible areas of native woodland (rising to 300 m at Shieldaig and 225 m at Glen Achall (NG820524)), but pine from Beinn Dearg (NH256808) might also be considered useful in this respect. These sites could also be useful in reinforcing and refining the effects of prevailing wind on asymmetric radial growth of pine.

Additional long chronologies would also be beneficial for the identification of spectral analysis cycles. Linderholm (2001) identifies 13 and 66-year period cycles which are suggested to be linked to variation in sea surface temperatures of the North Atlantic Ocean, pointing to a maritime influence, on decadal scales, of pine. The apparent absence of relationships to monthly climate data in sequences which nevertheless show strong cross-matching and high EPS may be a result of single month analysis. McCarrol (2003) found the correlation between ring width and temperature was increased by combining July and August temperature and this approach might be usefully examined further in the future. Further research examining modern clear-cut stands (where scars are readily examined) might also be considered desirable to help differentiate the response between Scots pine to fire and mammal scars. Such research would be useful to identify modern fire histories and possible relationships in the orientation of scars in Scotland. Similar study of pine stands on peatland following a known drainage event, would also be helpful to reinforce and clarify the response of pine. Concerns over the loss of the peatland record have been raised (Buckland 1993). Many peatlands have been drained and planted with Sitka spruce, lodgepole and Scots pine from the 1960s through to the early 1980s. Drainage on this scale has completely changed the nature of the effected bogs; the lowered water tables, topography of ridge and furrow, and shade cast by thicket-stage conifers has had a dramatic effect on the vegetation (Anderson 2001). Dendroclimatological analysis of pine growing on sites of known drainage would be useful to help refine the timing of growth release and change in response to climate.

Further analysis on subfossil pine is advocated to replicate the WRATH-9 chronology and its dating. Both Lageard *et al.* (2000) and Boswijk and Whitehouse (2002) comment on the eccentricity and lobate growth respectively for some of the subfossil pine found at their sites. Although no directional trends were investigated, this suggests the widespread potential for dendroaeology in the study of Holocene subfossil pine to establish palaeowind direction. It may also be significant that the majority of tephra identified in Holocene deposits from NW Europe originate from Iceland (Langdon and Barber 2004), which is located to its north-west and so also indicative of north-west winds operating at certain times. Further investigation into the effects of exposed and sheltered sites on the relationship between pine preservation, humification analysis and tephra layers would be useful to refine methodology for the use of pine as proxy for wind.

The results of this analysis also suggest a number of important implications for palaeo-temperature reconstructions from tree-ring density measurements, and particularly with regard to the direction of sampling. Prevailing wind is likely to have an influence on tree-ring densities as increased density is reported in flexed *pinus* spp. (Telewski 1990). Another factor perhaps significant in Scotland is whether pine within the same species but of different genetic origin, might produce different levels of ethylene, the plant growth regulator produced by trees in response to wind, flexure and bending (Telewski 1990).

4.4.4.3 Disturbance factors: germination and fire frequencies

The lack of relationship between germination and location identified is thought likely to be due to an absence of the location data from most modern pine sites and only a limited number of cross-matched subfossil samples. Studies on drained peatland have shown enhanced regeneration and better survival of saplings (Roy *et al.* 2000, Sarkkola *et al.* 2004), therefore pine recruitment may be expected to be influenced by variations in temperature, precipitation and wind, all of which also affect groundwater levels. A number of periods of recruitment (which could indicate a climatic trigger) are identified. The initiation of two phases of germination at Monadh Mor in *c.* 1901 and *c.* 1923 follow two consecutive wide pointer years in 1898/1899 and 1921/1922; Pitmaduthy also shows a phase of germination starting *c.* 1925. A phase of germination at Inshriach in *c.* 1947 follows three consecutive wide pointer years (for the SE area) in 1943/1944/1945. This relationship could be related to the regeneration of pine requiring two consecutive summers warmer than the "average" (Sirén 1961), but more data would be needed to substantiate this possible relationship. Research in Sweden suggests seed fall occurs over a short period, starting mid to late April with the peak period lasting just 18-28 days (Hannerz *et al.* 2002). The precise timings may be different in Scotland between the NW and the SE; however this implies that the wide dispersal of pine seed might be related to storminess at specific times of the year. This also implies that there might be a relationship between widespread germination and periods of storminess.

5 CONCLUSIONS

Scots pine in northern Scotland is at the oceanic edge of its world range. The number and range of chronologies in this research (9 peat substrate and 26 mineral substrate sites), compared using common methodologies, make this the largest dendroclimatological investigation on the growth of modern Scots pine in northern Scotland and the first to examine pine growing on peat. The occurrence of subfossil pine beyond its current northern limit in Scotland at latitude at 58º north indicates a time (between about 3500-2300 ^{14}C cal. yr BC) when the climate was different to our current climate. One hundred and four subfossil pines were collected from this area, and 49 (47%) of these from 7 sites were successfully cross-matched (Figure 79) and tentertivly dated (Table 8). This strongly supports the hypothesis that this cohort represents a broadly coeval expansion of Scots pine. Hpowever, previously overlooked earlier horizons in Northern of Scotland, may well contribute to the failure of some samples to cross-match. The probably precise dating of these pine provides the first insights into Neolithic climate change in Scotland at annual resolution. Evidence of the survival of Modern pine on bog at minimal growth rates (< 0.5 mm yr^{-1}, Figure 77) together with the demonstrated ability of Holocene Scots pine to germinate over a wide area (Figure 78) and rapidly change its growth rate to take advantage or cope with changes, reinforcing its character as a "durable pioneer".

5.1 Dendroclimatology of Scots pine

Considerable differences in the relationships of ring width and climate are found between Scots pine growing on mineral substrate in the NW and SE areas of northern Scotland (Table 14). Evidence from ten chronologies in the SE area indicate that winter temperature (in January and February) as well as summer temperature (in July and August) are the most important determinants of ring width (Figure 81). Ring width is also negatively correlated with rainfall in August at eight sites. Scots pine growing between 400 and 500 m altitude show the most significant relationships with these climatic factors. In contrast, pine at 9 sites in the NW area show far fewer relationships to monthly climate variables (Figure 82). The most common significant relationships in the NW area are positive ones with temperature and NAO in January and February, months when gales are especially common. The evidence is consistent with pine growth in the less oceanic SE area being increasingly limited by temperature nearer its altitudinal limits. The highest growth rates for pine occur at low altitude sites and lowest growth rates at higher sites in the NW area; this also highlights that the reduction in temperature in winter due to increased altitude and distance from the moderating effects of the ocean, may be critical in limiting tree growth near its northern margin. Two physiological mechanisms for the winter relationship of climate on tree growth are proposed: disruption to the epidermis and large scale needle loss in winter could reduce radial growth increment the following summer, and winter photosynthesis could be a significant positive factor on radial growth.

For the first time, characteristics of Modern Scots pine growing on peatland at the five sites; Abernethy, Eilean Sùbhainn, Pitmaduthy Moss, Inshriach Bog and Monadh Mor, are examined to identify the climate-growth relationships. The relationships between ring width and monthly climate data identified from pine growing on mineral substrate site are predominantly absent from pine growing on peat substrate, even from sites immediately adjacent to each other. Nevertheless, February NAO indices are found to have a positive influence on pine growth at three sites, and four sites show a positive growth response to temperature in October. Cross-matching between Monadh Mor and Pitmaduthy Moss (some 30 km apart) demonstrate a potential for the regional cross-matching of peat substrate chronologies and suggests that drainage of bog alters growth conditions to resemble those of pine on mineral substrate. Low radial growth rates ranging from 0.5 to 1 mm yr^{-1} on bog and mires compare to growth rates of ≥1.5 mm yr^{-1} on adjacent mineral substrate pine sites (Figure 76 and Figure 77). These results accord with tree growth on peatlands being limited by high water table and poor nutrient status. Scots pine growing on peat are found to almost instantly change radial growth rate in response to probable changes in water table, and this suggests they may have a critical role in helping to establish the relationship between water table in mires/bogs and climate.

Moving correlation functions find a change in the response of pine growing in both mineral and peat substrates to monthly climate data occurring from the 1920s, which is not fully understood. The change in response of bog pine may correspond with a general rising water-table culminating in a step shift to a wetter mire surface around the 1900s (Charman 2007). The reasons for the change in the response of pine growing on mineral substrate are less clear. However, changes in the radial growth rate of pine growing at the edge of Loch Maree suggest a probable response to different water levels, and highlights their potential use in reconstructions of past lake levels.

The earliest communities of bog pine at Abernethy, Eilean Sùbhainn and Pitmaduthy represent mature bog pine and are shown to have been established from the 1780s (although one tree germinated *c.* 1694), 1830s and 1880s, respectively. With the possible exception of one site at Abernethy, changes in radial growth indicate that all the sites of pine growing on peat have undergone disturbance such as fire and peat cutting. Fire is identified to have low incidence during the growth of pine on mire in Scotland which reduces this disturbance to the peat profile in comparison to much of Europe. In contrast to findings by Lageard (2000), who identified increases in ring width following fire scars from subfossil pine in England, mean reductions of 23% over a 2 year period and 31 % over a 20 year period in the subsequent radial growth of Scots pine were found.

5.2 The *c.* 3200 BC pine expansion and subsequent contraction

Seven subfossil pine chronologies from this research and two from earlier work (Daniell 1997) are cross-matched to form a chronology called WRATH-9. Although the full WRATH-9 fails to date, tentative cross-matching at 3139-2910 BC is achieved for a slightly shorter WRATH-9ED chronology which is consistent with radiocarbon dates. The failure of the longer WRATH-9 chronology, which spans *c.* 3175-2790 BC, suggests that some problems have yet to be resolved. Missing rings commonly found in the first and last 50 years of subfossil pine sequences suggest that Scots pine growing on bog is particularly vulnerable at these times. It is likely that this problem causes the less replicated beginning and end of the WRATH-9 chronology to be a few years out.

Significant advantages over most other dendrochronological research on subfossil trees, are that the samples are still *in situ* and many are preserved with bark (providing rare information on the precise timing of death). The cross-matching of subfossil pine shows its potential to provide precise information on the timing and nature of climatic change in Scotland. They provide a picture of an unexpectedly rapid, widespread and brief expansion of Scots pine across the far northern region of Scotland, from *c.* 3200 BC, which can be summarised as follows:

- germination at the three earliest sites (which extend over 60 km along the west coast of Scotland) probably occurred in the same year.
- initial germination occurred at all 9 sites that cross-match within 95 years
- after 200 years (probably between *c.* 3200-3000 BC), unfavourable conditions returned, resulting in the mortality of 73% of the trees cross-matched during the subsequent 100 year period.

- a remnant population of just six trees (from three sites) survived 360 years after the first germination, demonstrating the ability of pine to survive at minimal growth rates, well after climatic deterioration.
- sites were occupied for a single generation.
- the close timings and regional extent of germination, changes in radial growth and mortality provide strong evidence for cause by a regional change in climate

This research reverses the widely accepted conclusions of Bridge *et al.* (1990) that: "conventional dendrochronological methods are unlikely to produce reliable cross-matching" from subfossil pine in Scotland. The regional Neolithic pine chronology developed establishes a precise stratigraphic marker in northern Scotland offering a huge refinement to palaeoenvironmental investigations and significant advantages over the use of tephra for chronological dating. It does not support the theory that pine in northern Scotland died by a brief cataclysm and indicates the pine decline in palynology to be an imprecise target for the timing of climatic change (Figure 87). Assuming pine was not already present in the far north, its simultaneous germination suggests the long distance dispersal of Scots pine seed by strong wind. By this mechanism pine would be able to take advantage of short suitable periods for the colonisation of a bog surface. The remarkable alignment of the start dates of pine chronologies from Scotland and Ireland (Figure 85) highlight the further potential of calendar dating a probably coeval preserved horizon of pine found across west Ireland. Both areas are particularly oceanic and influenced more significantly by the Atlantic Ocean than other areas of Europe which does not show such distinct widespread horizons of subfossil pine.

The analysis of modern pine growing on mire in this research supports the hypothesis that climatic conditions in Scotland today are minimal for the growth of pine on mires. The evidence from the tree-rings is that extensive horizons of Scots pine in the mires of Scotland coincide with periods of transition from relatively dry to wet conditions. Broadly common changes in site wetness identified at a number of sites over the region indicate that such changes are related to regional climate change, rather than simply the result of local site changes. From the study of Scots pine growing on peat today, changes in water level on bog/mires are the most likely cause for the sudden germination and subsequent preservation of subfossil pine. While Scots pine growing on bog has the potential to exceed ages of 450 years, however ages over 300 years are rarely achieved, probably due to waterlogging.

Preservation of pine within bogs and mire and the absence of modern growth on peat surfaces suggest past climatic conditions were similar to those which exist today (which encourage peat formation) have predominantly prevailed. The occurrence of up to three horizons of preserved subfossil pine at some sites in the far north of Scotland (Table 5) suggests "short-term" change (from general conditions of pine preservation to those allowing growth) has occurred a number of times in the past. The potential to dendrochronologically date a number of other pine horizons across Scotland is highlighted by these results.

5.3 Dendroaeology

Asymmetric growth shown in modern Scots pine is found to be consistent in their relationship with the current W/SW prevailing wind. The mean orientation of maximum radial growth at eleven modern sites is found to coincide well with the UK's current W/SW prevailing wind (Figure 90). Using only samples with a mean difference between the maximum and minimum radii of over 10%, the mean difference from these sites is -24%. The results of this research strongly suggest that mean maximum radial growth in

Scots pines occurs in the lee of the prevailing wind. These findings are in accordance with two other studies on conifers (Bannan and Bindra 1970, Hamilton 2002). Windthrow, evident at four of the modern sites is also found to coincide with the direction of mean maximum radial growth. Two mechanisms for the cause of asymmetrical growth in pine are considered. Harsh winter gales may lead to loss and damage of a tree's needles/branches/trunk thereby reducing its photosynthetic potential and so its radial growth increment the following summer. This is conjectured as a mechanism by which the radial growth of tree on the side facing the wind might be reduced. Conversely, trees under stress from wind could respond by a thickening of growth rings in the lower stem close to the base (Wilson 1975) which could lead to increased radial growth to the lee of the wind.

Six coeval Neolithic sites consistently indicate a broadly northerly prevailing wind (direction ranging from a NE to NW). These subfossil pine samples are tentatively dated to between *c*. 3100-3000 BC suggesting an apparent reversal of prevailing wind at that time. The modern relationship between tree-ring growth and NAO suggest that a change of prevailing winds might be related to a southward incursion of the polar front in the eastern N. Atlantic. Phases of increased aeolian input into raised bog have been correlated with cold periods in northwest Europe, and increased winter storminess. These have also been suggested as linked to an expansion of the polar vortex (Björck and Clemmensen 2004, de Jong *et al.* 2006).

The results of moving correlation function analysis suggest that Scots pine in north western Scotland may be regarded as a proxy of NAO. Positive correlations of ring-width found between both NAO suggest a close relationship between these two factors. Moving correlation functions shows that chronologies in the SE area which extend before the 1920s lose their positive correlation with January and February temperature and NAO in February at this time. Chronologies from the NW area also show reductions and sometimes a loss of these positive correlations with temperature and NAO in the same months, occurring from the 1920s (Figure 92). Moving correlation functions show a clear and widespread change in the relationship between climate and the ring width of pine growing on both mineral and peat substrates occurs in the 1920s in Northern Scotland. The use of moving correlation functions is a significant step forward in dendroclimatological research, because it shows changes in the strength of the relationship of climate variables with ring width through time. Few places are as exposed to the passing lows of the Atlantic as Scotland. The relationship between NAO and the radial growth of pine appears strongest in the NW area of northern Scotland. However, variations in water table variations may reduce the strength of climate and tree growth relationships in pine in oceanic areas and particularly in Bog pine. The majority of the pine sites in the Oceanic NW area in this research are low altitude and so the relationship between climate and tree ring growth at higher altitude sites is currently unknown.

This research identifies an exciting new potential for tree-rings to provide calendar dated proxy information not only on temperature and precipitation, but also possibly wind. Understanding the response of Scots pine to climatic change is important to both dendroclimatology and commercial forestry. Changes in the way research is funded means there is a need to strengthen links between these disciplines (Downes *et al.* 2002). The precise calendar dated chronologies established for Neolithic subfossil pine provides a framework critical for future understanding of palaeoclimatological and archaeology investigations. The twinned present and past aspects of this research is also hoped to highlight the benefits of research on pine in Scotland and the rest of the British Isles. Additional research to clarify the relationships of variations in wind and NAO with the radial growth of Modern and Holocene pine is strongly advocated.

6 REFERENCES

Aaby, B, 1976 Cyclic climatic variations in climate over the past 5500 years reflected in raised bogs, *Nature*, **263**, 281-4.

Adams, J, Maslin, M, and Thomas, E, 1999 Sudden climatic transitions during the Quaternary, *Progress in Physical Geography*, **23**, 1-36.

Agee, J K, 1998 Fire and pine ecosystems, in *Ecology and Biogeography of Pinus* (ed H G Richter), Cambridge (University Press), 193-208.

Allen, J R L, 1992 Trees and their response to wind: mid Flandrian strong winds, Severn Estuary and inner Bristol Channel, southwest Britain, *Philisophical Transactions of the Royal Society of London*, **338**, 335-64.

Anderson, A and Harding, K, 2002 *The Age Structure of Scots pine bog woodland. Report to the Wet Woods LIFE Project*, Forestry Commission, Forest Research.

Anderson, D E, Binney, H A, and Smith, M A, 1998 Evidence for abrupt climatic change in northern Scotland between 3900 and 3500 calendar years BP, *The Holocene*, **8**, 97-103.

Anderson, R, 2001 *Deforesting and restoring Peat Bogs: A review*, Forestry Commission, Forestry Commission Technical Paper No, **32**.

Anon, 1964a Liability of trees on peat to wind-throw, *Scottish Forestry*, **18**, 38-43.

Anon, 1964b *Physico-Geographical Atlas of the World*, Moscow (Akad. Nauk (in Russain).

Appenzeller, C, 1999 Reconstruction of decadal climate variability: North Atlantic Oscillation, in *Swiss Climate Summer School*, (University of Bern),

Arkle, P J and Nixon, C, 1996 Structure and growth characteristics of Scots pine *Pinus sylvestris* (L.) in long term monitoring plots within the Black Wood of Rannoch native pinewood, *Scottish Forestry*, **50**(3), 145-50.

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

Ågren, J and Zackrisson, O, 1990 Age and size structure of *Pinus sylvestris* populations on mires in central and northern Sweden, *Journal of Ecology*, **78**, 1049-62.

Baillie, M G L, 1982 *Tree-Ring Dating and Archaeology*, London (Croom-Helm).

Baillie, M G L, 1990 Checking back on an assemblage of published radiocarbon dates, *Radiocarbon*, **32**, 361-6.

Baillie, M G L, 1991 Suck in and smear: two related chronological problems for the 90s, *Journal of Theoretical Archaeology*, **2**, 12-6.

Baillie, M G L, 1995a *A Slice Through Time - dendrochronology and precision dating*, London (Batsford).

Baillie, M G L, 1995b Dendrochronology and the chronology of the Irish Bronze Age, in *Ireland in the Bronze Age* (eds J Waddell, and E Shee-Twohig) (Stationary Office), 30-7.

Baillie, M G L and Munro, M A R, 1988 Irish tree rings, Santorini and volcanic dust veils, *Nature*, **332**, 344-6.

Baillie, M G L and Pilcher, J R, 1973 A simple cross-dating program for tree-ring research, *Tree-ring Bulletin*, **33**, 7-14.

Bannan, M W and Bindra, M, 1970 The inflence of wind on ring width and cell length in conifer stems, *Canadian Journal of Botany*, **48**, 255-9.

Barber, K E, 1982 Peat bog stratigraphy as a proxy climate record, in *Climatic Change in Later Prehistory* (ed A F Harding), Edinburgh (Edinburgh University Press), 103-33.

Barber, K E, Langdon, P G, and Blundell, A, 2008 Dating the Glen Garry tepra: a widespread late-Holocene marker horizon in the peatlands of northern Britain, *The Holocene*, **18**(1), 31-43.

Barber, K E, Zolitschka, B, Tarasov, P, and Lotter, A F, 2004 Atlantic to Urals - the Holocene climatic records of Mid-Latitude Europe, in *Past climate variability through Europe and Africa* (eds R W Battarbee, F Gasse, and C E Stickley) (Springer), Developemtns in Paleoenvironmental Research, 6.

Barnett, C., Hossell, J, Perry, M, Procter, C, and Hughes, G, 2006 *A handbook of climate trends across Scotland*, 1-62 . (Scotland & Northern Ireland Forum for Environmental Research). SNIFFER project CC03.

Bartholin, T S and Karlen, W, 1983 Dendrokronologi: Lappland, *Dendrokronologiska Sallpets Meddelanden*, **5**, 3-16.

Bartholomew, A, Malcolm, D C, and Nixon, C J, 2001 The Scots pine population at Glen Loyne, Invernesshire: present condition and regenerative capacity, *Scottish Forestry*, **55**(3), 141-8.

Bennett, K D, 1984 The post-glacial history of *Pinus sylvestris* in the British Isles, *Quaternary Science Reviews*, **3**, 133-55.

Bennett, K D, 1989 The post-glacial history of *Pinus sylvestris* in the British Isles: A provisional map of forest types for the British Isles 5000 years ago, *Journal of Quaternary Science*, **4**, 141-4.

Bennett, K D, 1995 Postglacial dynamics of pine (*Pinus sylvestris* L.) and pinewoods in Scotland, in *Our Pinewood Heritage* (ed J R Aldhouse), Edinburgh (Forestry Commission, Royal Society for the Protection of Birds), 22-39.

Bennett, K D, 2005 *Map of distribution of Scottish pine remains*, Public communication.

Bennett, K D, Tzadakis, P C, and Willis, K J, 1991 Quaternary refugia of north European trees, *Journal of Biogeography*, **16**, 503-40.

Binney, H. A., 1997 Holocene environmental change in the Scottish Highlands: multiproxy evidence from blanket peats, Unpublished PhD thesis, London Guildhall University.

Biondi, F, 1997 Evolutionary and moving response functions in dendroclimatology, *Dendrochronologia*, **15**, 139-50.

Biondi, F, 2000 Are climate-tree growth relationships changing in north-central Idaho?, *Arctic Antarctic and Alpine Research*, **32**, 111-6.

Biondi, F and Waikul, K, 2004 Dendroclime2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies, *Computer & Geosciences*, **30**, 303-11.

Birks, H H, 1972 Studies in the Vegetational History of Scotland.III. A Radiocarbon-dated pollen diagram from Loch Maree, *New Phytologist*, **7**(1), 731-54.

Birks, H H, 1975 Studies in the vegetational history of Scotland. IV. Pine stumps in Scottish blanket peats, *Philisophical Transactions of the Royal Society of London*, **B**, 181-226.

Birks, H H, 1978 Studies in the vegetational history of Scotland. V. Late Devensian and early Flandrian pollen and macrofossil stratigraphy at Abernethy Forest, Inverness-shire, *New Phytologist*, **80**, 455-84.

Birks, H J B, 1988 Long-term Ecological change in the British Uplands, in *Ecological change in the Uplands* (eds M B Usher, and D B A Thompson), Oxford (Blackwell Scientific Publications), 37-56.

Birks, H J B, 1989 Holocene isochrone maps and patterns of tree-spreading in the British Isles, *Journal of Biogeography*, **16**, 503-40.

Birks, H J B, 1996 Great Britain - Scotland, in *Palaeoecological events during the last 15 000 years* (eds B E Berglund, H J B Birks, M Ralska-Jasiewiczowa, and H E Wright), Chichester (John Wiley), 95-143.

Birks, H J H, 1983 Late-Quaterary vegetational history of the Inner Hebrides, *Proceedings of the Royal Society of Edinburgh 269.*

Birse, E L, 1971 *Assessment of climatic conditions in Scotland. Bioclimate sub-regions*, Aberdeen (The Macaulay Institute for Soil Research).

Birse, E L, and Dry, F T, 1970 *Assessment of climatic conditions in Scotland 1. Based on accumulated temperature and potential water deficit*, 1-25 .Aberdeen (The Macaulay Institute for Soil Research).

Birse, E L, and Robertson, L, 1970 *Assessment of climatic conditions in Scotland 1. Based on exposure and accumulated frost*, Aberdeen (The Macaulay Institute for Soil Research).

Björck, S and Clemmensen, L B, 2004 Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia?, *The Holocene*, **14**(5), 677-88.

Blackford, J J, 1993 Peat bogs as sources of proxy climate data: past approches and future research, in *Climatic change and Human Impact on the Landscape* (ed F M Chambers), London (Chapman and Hall), 47-56.

Blackford, J J and Chambers, F M, 1995 Proxy climate record for the last 1000 years from Irish blanket peat and a possible link to solar variability, *Earth and Planetary Science Letters* (133), 145-50.

Blackford, J J, Edwards, K J, Dugmore, A J, Cook, G T, and Buckland, P C, 1992 Icelandic volcanic ash and the mid-Holocene Scots pine (*Pinus sylvestris*) pollen decline in northern Scotland, *Holocene*, **2**(3), 260-5.

Blasing, T J, Solomon, A M, and Duvick, D N, 1984 Response functions revisited, *Tree-ring Bulletin*, **44**, 1-15.

Boggie, R, 1972 Effect on water-table height on root development of *Pinus contorta* on deep peat in Scotland, *Oikos*, **23**, 304-12.

Bohn, U, and Neuhäusl, R, 2000 *Map of the natural vegetation of Europe*, Bonn-Bad Godesberg, Germany (Bundesamt für Naturschutz).

Bond, G C, Showers, W, Cheseby, M, Lotti, R, Almasi, P, and deMenocal, P, 1997 A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates, *Science*, **278**, 1257-66.

Booth, T C, 1984 Natural regeneration in the native pinewoods of Scotland: a review of principles and practice, *Scottish Forestry*, **38**, 33-41.

Boswijk, G and Whitehouse, N J, 2002 Pinus and Prostomis: a dendrochronological and palaeoentomological study of a mid-Holocene woodland in eastern England, *The Holocene*, **12**, 585-96.

Bosworth, G., 2005 High-resolution palaeoenvironmental investigation on Holocene mires in the Baltic region, Unpublished PhD thesis, University of Gloucestershire.

Box, G E P, and Jenkins, G M, 1970 *Time Series Analysis, Forecasting and Control*, San Francisco (Holden-Day).

Bradbury, I K and Malcolm, D, 1978 Dry matter accumulation by *Picea sitchensis* saplings during winter, *Canadian Journal of Forest Research*, **8**, 207-13.

Bradshaw, R H W, 1987 The early impact of man, in *The heritage of Clonmacnoise* (ed M Turbridy), Co. Offaly, Ireland (Environmental Sciences Unit, Trinity College).

Bradshaw, R H W, 1993 Forest response to Holocene climatic change: equilibrium or non-equilibrium., in *Climate change and human impact on the landscape: studies in palaeoecology and ennironnaental archaeology* (ed F M Chambers), London (Chapman & Hall), 57-65.

Bradshaw, R H W and Zackrisson, O, 1990 A two thousand year history of a northern Swedish boreal forest stand, *Journal of Vegetation Science*, **1**, 519-28.

Bragg, O. M., 1982 The acrotelm of Dunn Moss, Unpublished PhD thesis, University of Dundee.

Brække, H F, 1987 Nutrient relationship in forest stands: effects of drainage and fertilization on surface peat layers, *Forest Ecology and Management*, **21**, 269-84.

Bridge, M C, Haggart, B A, and Lowe, J J, 1990 The History and Palaeoclimatic significance of subfossil remains of *Pinus sylvestris* in blanket peats from Scotland, *Journal of Ecology*, **78**, 77-99.

Briffa, K. R., 1984 Tree-Climate Relationships and Dendroclimatological Reconstruction in the British Isles, Unpublished PhD thesis, University of East Anglia.

Briffa, K R, 2000 Annual climate variability in the Holocene: interpreting the message of ancient trees, *Quaternary Science Reviews*, **19**(1-5), 87-105.

Briffa, K R, Bartholin, T S, Eckstein, D, Jones, P D, Karlen, W, Schweingruber, F H, and Zetterberg, P, 1990 A 1,400-year tree-ring record of summer temperatures in Fennoscandia, *Nature*, **346**, 434-9.

Briffa, K R and Cook, E R, 1990 Methods of response function analyisis, in *Methods of Dendrochronology* (eds E R Cook, and L Kairiukstis), Dordrecht, The Netherlands (Kluwer), 165-78.

Briffa, K R, Jones, E W, Pilcher, J R, and Hughes, M K, 1988 Reconstructing Summer Temperatures in Northern Fennoscandinavia Back to A.D. 1700 Using Tree-Ring Data from Scots Pine, *Arctic and Alpine Research*, **20**(**4**), 385-94.

Briffa, K R and Jones, P D, 1990 Basic chronology statistics and assessment, in *Methods of Dendrochronology. Applications in the environmental science* (eds E R Cook, and L A Kairiukstis), Dordrecht (Kluwer Academic Publishers), 137-52.

Briffa, K R, Jones, P D, Schweingruber, F H, Karlen, W, and Shyatov, S G, 1996 Tree-ring variables as proxy-indicators: Problems with low-frequency signals., in *Climatic Variations and Forcing Mechanisms of the Last 2000 Years* (eds P D Jones, R S Bradley, and J Jouzel) (NATO), *ASI Series I41*, 9-41.

Briffa, K R, Jones, P D, Wigley, T M L, Pilcher, J R, and Baillie, M G L, 1983 Climate reconstruction from tree rings: Part 1, Basic methodology and preliminary results for England, *Journal of Climatology*, **3**, 233-42.

Briffa, K R, Osborn, T J, and Schweingruber, F H, 2004 Large-scale temperature inferences from tree-rings: A review, *Global and Planetary Change*, **40**, 11-26.

Briffa, K R, Schweingruber, F H, Jones, P D, Osborn, T J, Shiyatov, S G, and Vaganov, E A, 1998 Reduced sensitivity of recent tree-growth to temperature at high northern latitudes, *Nature*, **391**(678), 682.

Brockmann-Jerosch, H, 1913 Der einfluss des Klimacharakters auf die Verbreitung der Pflanzen und Pflanzgesellachaften, *Beiblatt zu den Botaniscen Jahrbüchen*, **109**, 19-43.

Bronk Ramsey, C, 1995 Radiocarbon calibration and analysis of stratigraphy: The OxCal program, *Radiocarbon*, **37**(2), 425-30.

Bronk Ramsey, C, 2001 Development of the radiocarbon calibration program OxCal, *Radiocarbon*, **43**(2a), 355-63.

Bronk Ramsey, C, Van de Plicht, J, and Weninger, B, 2001 'Wiggle matching' radiocarbon dates, Radiocarbon, 43 (2A) 381-389, *Radiocarbon*, **43**(2A), 381-9.

Brown, D. M., 1991 Studies on *Pinus sylvestris* L. from Garry Bog, Co. Antrim, Unpublished MSc thesis, Queen's University Belfast.

Brown, D M and Baillie, M G L, 1992 Construction and dating of a 5000 year English bog oak tree-ring chronology, in *Tree Rings and Environment* (eds T S Bartholin, B E Berglund, D Eckstein, and F H Schweingruber), Lund (Lund University), Lundqua report 34, 72-5.

Buckland, P C, 1993 Peatland archaeology: a conservation resource on the edge of extinsion, *Biodiversity and Conservation*, **2**, 513-27.

Burke, W, 1975 Fertilizer and other chemical losses in drainage water from blanket bog, *Irish Journal of Agricultural Research*, **14**, 163-78.

Burnand, J, 1976 Quercus pubescens-Wäldeer und ihre ökologischen Grenzen im Wallis (Zentralalpen), Dissertation, ETH Zürich.

Burton, J D and Smith, D M, 1972 *Guying to prevent wind sway influences Loblolly pine growth and wood properties*, US Forestry Service Research Paper, **SO-80**.

Butler, S, 1992 X-radiography of archaeological soil and sediment profiles, *Journal of Archaeological Science*, **19**(15), 1-19.

Carlisle, A and Brown, A, 1968 Biological flora of the British Isles. *Pinus sylvestris* L., *Journal of Ecology*, **56**, 269-307.

Carrer, M and Urbinati, C, 2006 Long-term change in the sensitivity of tree-ring growth to climate forcing in *Larix decidua*, *New Phytologist*, **170**(4), 861-72.

Caseldine, C, Hatton, J, Huber, U, Chiverrell, R, and Woolley, N, 1998 Assessing the impact of volcanic activity on mid-Holocene climate in Ireland: the need for replicated data, *The Holocene*, **8**, 105-11.

Caseldine, C, Thompsen, G, Langdon, C, and Hendon, D, 2005 Evidence for an extream climatic event on Achill Island, Co. Mayo, Ireland around 5200-5100 cal. yr BP, *Journal of Quaternary Science*, **20**(2), 169-78.

Caulfield, S, O'Donnell, R G, and Mitchell, P I, 1998 ^{14}C dating of a Neolithic field system at Céide Fields, Country Mayo, Ireland, *Radiocarbon*, **40**, 629-40.

Chambers, F M, Barber, K E, Maddy, D, and Brew, J, 1997a A 5500-year proxy-climate and vegetation record from blanket mire at Talla Moss, Borders, Scotland, *Holocene*, **7**, 391-9.

Chambers, F M, Legeard, J G A, Boswijk, G, Thomas, P A, Edwards, K J, and Hillam, J, 1997b Dating prehistoric bog-fires in northern England to calendar years by long-distance cross-matching of pine chronologies, *Journal of Quaternary Science*, **12**(3), 253-6.

Chantal, M, Leinonem, K, Kuuluvainen, T, and Cescatti, A, 2003 Early response of *Pinus sylvestris* and *Picea abies* seedlings to an experimental canopy gap in a boreal spruce forest, *Forest Ecology and Management*, **176**, 321-36.

Chapin, F S, McGraw, J B, and Shaver, G R, 1989 Competition causes regular spacing of alder in Alaskan shrub tundra, *Oecologia*, **79**, 412-6.

Charman, D J, 1992 Blanket mire formation at the Cross Lochs, Sutherland, northern Scotland, *Boreas*, **21**, 53-72.

Charman, D J, 1994 Late-glacial and holocene vegetation history of the flow country, Northern Scotland, *New Phytologist*, **127**(1), 155-68.

Charman, D J, 2007 Summer water deficit variability controls on peatland water-table changes: implications for Holocene palaeoclimate reconstructions, *The Holocene*, **17**(2), 217-27.

Charman, D J, Aravena, R, and Warner, B, 1992 Isotope geochemistry of gas and water samples from deep peats in Boreal Canada, *Suo Mires & Peat*, **43**, 199-201.

Charman, D J, West, S, Kelly, A, and Grattan, J, 1995 Environmental change and Tephra Deposition: The Strath of Kildonan, Northern Scotland, *Journal of Archaeological Science*, **22**, 799-809.

Cheddadi, R, Vandramin, G G, Litt, T, François, L, Kageyama, M, Lorentz, S, Laurent, J, de Beaulieu, J, Sadori, L, Jost, A, and Lunt, D, 2006 Imprints of glacial refugia in the modern genetic diversity of *Pinus sylvestris*, *Global Ecology and Biogeography*, **15**, 271-82.

Clymo, R S and Reddaway, E J F, 1971 Productivity of *Sphagnum* (bog-moss) and peat accumulation, *Hidrobiologia*, **12**, 181-92.

Conkey, L E, 1982, in *Climate from Tree-Rings* (eds M K Hughes, P M Kelly, J R Pilcher, and V C LaMarche), Cambridge University Press.

Cook, E. R., 1985 A time series analysis approach to tree ring standardization, Unpublished PhD thesis, The University of Arizona.

Cook, E R, 1987 The decomposition of tree-ring series for environmental studies, *Tree-ring Bulletin*, **47**, 37-59.

Cook, E R and Briffa, K R, 1990 A comparison of some tree-ring standardization methods, in *Methods of Dendrochronology. Applications in the environmental science* (eds E R Cook, and L A Kairiukstis), Dordrecht (Kluwer Academic Publishers), 153-62.

Cook, E R, Briffa, K R, Shiyatov, S G, and Mazepa, V, 1990 Tree-ring standardization and growth-trend estimation, in *Methods of Dendrochronology. Applications in the environmental science* (eds E R Cook, and L A Kairiukstis), Dordrecht (Kluwer Academic Publishers).

Cook, E R and Peters, K, 1981 The smoothing spline: A new approch to standardizing forest interior tree-ring width series for dendroclimatic studies, *Tree-ring Bulletin*, **41**, 45-53.

Craighead, F C and Gilbert.V.C., 1962 The effects of Hurricane Donna on the vegetation of southern Florida, *Q.Jl.Florida Acad.Sci.*, **21**, 1-28.

Crawford, R M M, 2000 Ecological hazards of oceanic environments, *New Phytologist*, **147**, 257-81.

Cucchi, V, Meredieu, C, Stokes, A, Berthier, S, Bert, D, Najar, M, Denis, A, and Lastennet, R, 2004 Root anchorage of inner and edge trees in stands of Maritime pine (*Pinus pinaster* Ait.) growing in different podzolic soil conditiona, *Tree - Structure and Function*, **18**(4), 460-6.

D'Arrigo, R D, Kaufmann, R K, and Davi, N, 2004 Thresholds for warming-induced growth decline at elevational treeline in Yukon Territory, Canada, *Global Biogeochemical Cycles*, **18.**

Dang, Q L and Lieffers, V J, 1989 Climate and annual ring grwoth of black spruce in some Alberta peatlands, *Canadian Journal of Botany*, **67**, 1885-9.

Daniell, J. R. G., 1992 A Dendrochronological study of subfossil *Pinus sylvestris* L. stumps from peat deposits at Badanlock in the far North of Scotland, Unpublished MSc thesis, Durham University.

Daniell, J. R. G., 1997 The Late-Holocene Palaeoecology of Scots Pine (*Pinus sylvestris* L.) in North-West Scotland, Unpublished PhD thesis, Durham University.

Dauchot-Dehan, M, van Strydonck, M, and Heylen, J, 1981 Institut Royal du Patrimonie Artistique radiocarbon dates VIII, *Radiocarbon*, **23**, 345-51.

Dawson, A G, Hickey, K, Holt, T, Elliott, L, Dawson, S, Foster, I D L, Wadhams, P, Jonsdottir, I, Wilkinson, J, McKenna, J, Davis, N R, and Smith, D E, 2002 Complex North Atlantic Oscillation (NAO) Index signal of historic North Atlantic storm-track changes, *The Holocene*, **12**, 363-9.

Dawson, A G, Hickey, K, McKenna, J, and Foster, I D L, 1997 A 200-year record of gale frequency, Edinburgh, Scotland: a possible link with high magnitude volcanic eruptions, *The Holocene*, **7**, 337-41.

de Jong, R, Björck, S, Björkman, L, and Clemmensen, L B, 2006 Storminess variation during the last 6500 years as reconstructed from ombrotrophic peat bog in Halland, southwest Sweden, *Journal of Quaternary Science*, **21**, 905-19.

Debain, S, Curt, T, and LePart, J, 2003 Seed mass, seed dispersal capacity, and seedling performance in a *Pinus sylvestris* population, *Ecoscience*, **10**(2), 168-75.

Desplanque, C, Rolland, C, and Schweingruber, F H, 1999 Influence of species and abiotic factors on extreme tree ring modulation: *Picea abies* and *Abies alba* in Tarentaise and Maurienne (French Alps), *Trees*, **13**(4), 218-27.

Dickson, J H, 1988 Post-glacial pine stumps in Central Scotland, *Scottish Forestry*, **42**, 192-9.

Dittus, W P J, 1985 The incluence of cyclones on the dry evergreen forest of Sri Lanka, *Biotropica*, **17**, 1-14.

Doutt, J K, 1941 Wind prunning and salt spray as factors in ecology, *Ecology*, **22**(2), 195-6.

Downes, G M, Wimmer, R, and Evans, R, 2002 Understanding wood formation: gains to commercial forestry through tree-ring reseach, *Dendrochronologia*, **20**, 37-51.

Drobyshev, I, Niklasson, M, and Angelstam, P, 2004 Contrasting Tree-ring Data with Fire Record in a Pine-dominated Landscape in the Komi Republic (Eastern European Russia): Recovering a Common Climate Signal, *Silva Fennica*, **38**(1), 43-53.

Dubois, A D and Ferguson, D K, 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.

Dugmore, A J, 1989 Icelandic volcanic ash in Scotland, *Scottish Geographical.Magazine*, **105**(3), 168-72.

Dugmore, A J, Cook, E R, Shore, J S, Newton, A J, Edwards, K J, and Larson, G, 1995a Radiocarbon dating tephra layers in Britain and Iceland, *Radiocarbon*, **37**, 379-88.

Dugmore, A J, Larson, G, and Newton, A J, 1995b Seven tephra isochrones in Scotland, *The Holocene*, **5**, 257-66.

Dupont, L. M., 1985 Temperature and Rainfall Variation in a Raised bog Ecosystem, Unpublished PhD thesis, University of Amsterdam.

Dupont, L M, 1986 Temperature and rainfall variations in the Holocene based on comparative palaeoecology and isotope geology of a hummock and a hollow (Bourtangerveen, The Netherlands), *Review of Palaeobotany and Palynology*, **48**, 71-159.

Durno, S. E., 1967 Scottish Woodland History since Boreal Time as recorded by Pollen Analysis of peat, Unpublished PhD thesis, University of Aberdeen.

Dwyer, R and Mitchell, F, 1997 Investigation of the environmental impact of remote volcanic activity on North Mayo, Ireland, during the mid-Holocene, *Holocene*, **7**(1), 113-8.

Eckstein, D, Ogden, J, Jacoby, G C, and Ash, J, 1981 Age and growth rate determination in tropical trees: The application of dendrochronological methods, in *Age and growth rate of tropical trees: new directions for research* (eds F Bormann, and G Berlyn) (Yale University), School of Forestry and Environmental Studies Bull. No. 94, 83-106.

Edwards, C and Mason, W L, 2006 Stand structure and dynamics of four native Scots pine (*Pinus sylvestris* L.) woodlands in northern Scotland, *Forestry*, **79**(3), 261-77.

Edwards, K J, Dugmore, A J, Buckland, P C, Blackford, J J, and Cook, G T, 1996 Hekla-4 ash, the pine decline in Northern Ireland and the effective use of tephra isochrones: a comment on Hall, Pilcher and McCormac, *The Holocene*, **6**, 495-6.

Eilmann, B, Weber, P, Rigling, A, and Eckstein, D, 2006 Growth reactions of *Pinus sylvestris* L. and *Quercus pubescens* Willd. to drought years at a xeric site in Valais, Switzerland, *Dendrochronologia*, **23**, 121-32.

Eliseu, H, 1942 *Nocoes de Silvicultura*, 2nd edn, Leira.

Ellenberg, H, 1988 *Vegetation ecology of Central Europe*, Cambridge (Cambridge University Press).

Engelmark, O, 1984 Forest fires in the Munddus national park (northern Sweden) during the past 600 years, *Canadian Journal of Botany*, **62**, 893-8.

Engelmark, O, 1987 Fire history correlations to forest type and topography in northern Sweden, *Annales Botanici Fennici*, **24**(4), 317-24.

Engelmark, O, 1993 Early Post-Fire Tree regeneration in a Picea-Vaccinium Forest in Northern Sweden, *Journal of Vegetation Science*, **4**(6), 791-4.

Engelmark, O, Kullman, L, and Bergeron, Y, 1994 Fire and age structure of Scots pine and Norway srruce in northern Sweden during the past 700 years, *New Phytologist*, **126**, 163-8.

Ennos, R A, 1991 Genetic variation in Caledonican pine populations: origins, explotation and conservation, in *Genetic variation in European populations of forest trees* (eds G Muller-Starch, and Ziehe.M.), Frankfurt (Sauerlander's Verlag), 235-49.

Ennos, R A and Perks, M P, 1995 Provernance and family variation for height growth, branching frequency and flushing date in native Scots pine, in *Our Pinewood Heritage* (ed J R Aldhouse), Glasgow (Bell & Bain), 252.

Ennos, R A, Sinclair, W T, Morman, J, and Perks, M P, 1995 Genetics and Conservation of Native Pinewoods, *Sylva*, **58**, 13-6.

Ennos, R A, Sinclair, W T, and Perks, M P, 1997 Genetic insights into the evolution of Scots pine, *Pinus sylvestris* L., in Scotland, *Botanical Journal of Scotland*, **49**, 257-65.

Ennos, R A, Worrell, R, and Malcolm, D C, 1998 The genetic management of native species in Scotland, *Forestry*, **71**(1), 1-23.

Eronen, M, Zetterberg, P, Briffa, K R, Linderholm, H W, 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**, 673-80.

Forrest, G I, 1992 Conservation of the native pinewoods of Scotland: the role of gene pool analysis, *Scottish Forestry*, **46**, 194-201.

Fossitt, J. A., 1990 Holocene vegetational history of the Western Isles, Scotland, Unpublished PhD thesis, University of Cambridge.

Fourt, D R, Donald, D G M, Jeffers, Jn R, and Binns, W O, 1995 Corsican Pine (*nigra var. maritima* (Ait.) Melville) in Southern Britain: A study of growth and site factors, *Forestry*, **44**, 189-207.

Franzén, L, 1987 *Peat in Sweden - A method to calculate the resources*, Department of Physical Geography, Gothenburg University, **GUNI Rapport 21**.

Freléchoux, F, Buttler, A, and Gillet, F, 2000 Dynamics of bog-pine-dominated mires in the Jura Mountains, Switzerland: a tentertive scheme based on synusial phytosociology, *Folia Geobotanica*, **35**, 273-88.

French, D D, Miller, G R, and Cummins, R P, 1997 Recent development of High-Altitude *Pinus sylvestris* scrub in the northern Cairngorm mountains, Scotland, *Biological Conservation*, **79**, 133-44.

Friedrich, M, Kromer, B, Kaiser, K F, Spurk, M, Hughen, K A, and Johnsen, S J, 2001 High-resolution climate signals in the Bølling-Allerød Interstadial (Greenland Interstadial 1) as reflected in European tree-ring chronologies compared to marine varves and ice-cores, *Quaternary Science Reviews*, **20**, 1223-32.

Friedrich, M, Kromer, B, Spurk, M, Hofmann, J, and Kaiser K F, 1999 Paleo-environmental and radiocarbon calibration as derived from Lateglacial/Early Holocene tree-ring chronoligies, *Quaternary International*, **61**, 27-39

Fritts, H C, 1966 Growth-ring of trees: Their correlation with climate, *Science*, **154**, 973-9.

Fritts, H C, 1971 Dendroclimatology and dendroecology, *Quaternary Research*, **1**, 419-49.

Fritts, H C, 1976 *Tree Rings and Climate*, New York (New York Academic Press).

Fritts, H C, 1999 *PRECON Version 5.1: A statistical model for analyzing the tree-ring reponse to variations in climate*, Tuscon (Laboratory of Tree-Ring Research, University of Arizona).

Fritts, H C, Smith, D G, Cardis, J W, and Budelsky, C A, 1965 Tree-ring characteristics along a vegetational gradient in northern Arizona, *Ecology*, **46**, 393-401.

Froyd, C A, 2005 Fossil stomata reveal early pine presence in Scotland: Implications for Postglacial colonization analysis, *Ecology*, **86**(3), 579-86.

Froyd, C A, 2006 Holocene fine in the Scottish Highlands: evidence frm macroscopic charcoal records, *The Holocene*, **16**(2), 235-49.

Gear, A. J., 1989 Holocene vegetation history and the palaeoecology of *Pinus sylvestris* in northern Scotland, Unpublished PhD thesis, University of Durham.

Gear, A J and Huntley, B, 1991 Rapid Changes in the Range Limits of Scots Pine 4000 Years Ago, *Science*, **251**, 544-7.

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

Godwin, H and Willis, E H, 1960 Cambridge University natural radiocarbon measurements II, *American Journal of Science Radiocarbon Supplement*, **2**, 62-72.

González, I G, 2001 Weiser: a computer program to identify event and pointer years in dendrochronological series, *Dendrochronologia*, **19**(2), 1-6.

Goode, D A and Ratcliffe, D A, 1977 Peatlands (ed D A Ratcliffe), Cambridge (Cambridge Univ. Press).

Goucher, T and Nixon, C, 1996 A study of age structure in three native pinewoods in Lochaber, *Scottish Forestry*, **50**(1), 17-21.

Grace, J, 1977 *Plant Response to Wind*, London (Academic Press).

Grace, J, 1989 Tree Lines, *Philisophical Transactions of the Royal Society of London*, **B324**, 233-45.

Grace, J, Berninger, F, and Nagy, L, 2002 Impacts of Climate Change on Tree Line, *Annals of Botany*, **90**, 537-44.

Grace, J and Norton, D A, 1990 Climate and Growth of *Pinus sylvestris* at its upper altitudinal limit in Scotland: evidence from tree growth-rings, *Journal of Biogeography*, **78**, 601-10.

Greene, D F and Johnson, E A, 1989 A model of wind dispersal of winged or plumed seeds, *Ecology*, **70**(2), 339-47.

Grieser, J, 2005 *New_LocClim: Local Monthly Climate Estimator, Version 1.5. Environment and Natural Resources Working Paper Number 20.*, Rome, Italy (Food and Agriculture Organization of the United Nations).

Gunnarsson, U, Malmer, N, and Rydin, H, 2002 Dynamics or constancy in *Sphagnum* dominated mire ecosystems? A 40 -year study, *Ecography*, **25**, 685-704.

Gutiérrez, E, 1989 Dendroclimatological Study of *Pinus sylvestris* L. in Southern Catalonia (Spain), *Tree-ring Bulletin*, **49**, 1-9.

Günther, H, Roseenthal.W., Stawarz, M, Carretero, J C, Gomez, M, Lozano, I, Serrano, O, and Reistad, M, 1998 The wave climate of the northeast Atlantic over the period 1955-1994: the WASA wave hindcast, *The Global Atmosphere and Ocean System*, **6**, 121-63.

Hall, V A, Pilcher, J R, and McCormac, F G, 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.

Hamilton, W L, 2002 *Assessed Potential of Conifers as Proxy Paleo-wind*, American Geophysical Union, Fall Meeting 2002.

Hannerz, M, Almqvist, C, and Hörnfeldt, R, 2002 Timing of Seed Dispersal in *Pinus sylvestris* Stands in Centra Sweden, *Silva Fennica*, **36**(4), 757-65.

Harper, J L, 1977 *Population biology of plants*, New York, USA (Academic Press).

Harrison, S J, 1997 Changes in the Scottish climate, *Botanical Journal of Scotland*, **49**, 287-300.

Harrison, S J and Digerfeldt, G, 1993 European lakes as palaeohydrological and palaeoclimatic indicators, *Quaternary Science Reviews*, **12**, 233-48.

Hayes.A., 1993 *Archaeology of the British Isles* , London (BT Batsford Ltd).

Hicks, S, Eckstein, D, Schmitt, U, Tuovinen, M, Jalkanen, R, McCarroll, D, Pawellek, P, Edouard, J-L, Gagen, M, Birks, H H, Serres, R, Hyvärinen, H, and Nivala, V, 2000 Forest response to environmental stress at timberlines: sensitivity of Northern Alpine and Mediterranean forest limits to climate, in *Proc. Europ. Climate Science Conf., Vienna, 19-23 October 1998*, (Austrian Fedral Ministry of Science and Transport).

Hillam, J, 1998 *Dendrochronology: Guidelines on producing and interpreting dendrochronological dates*, London (English Heritage).

Hobbs, N B, 1986 Mire morphology and the properties and behaviour of some British and foreign peats, *Quaterley Journal of Engineering Geology*, **19**, 7-80.

Hodge, S and Pepper, H, 1998 *The prevention of Mammal Damage to Trees in Woodland*, Forestry Practice, Forestry Commission, Practice Note, **FCPN3**.

Holmes, R L, Adams, R K, and Fritts, H C, 1986 *Tree-Ring Chronologies of Western America: California, Oregon and Northern Great Basin with Procedures Used in the Chronology Development Work Including Users Manuals for Computer Programs COFECHA and ARSTAN*, 1-182 .Tuscon (Laboratory of Tree-Ring Research, University of Arizona). Chronology Series IV.

Hornung, M and Newson, M D, 1986 Upland afforestation influences on stream hydrology and chemistry, *Soil Use Management*, **2**, 61-5.

Huang, J, Bergeron, Y, Denneler, B, Berninger, F, and Tardif, J, 2007 Response of Forest Trees to Increased Atmospheric CO_2, *Critical Reviews in Plant Sciences*, **26**, 265-83.

Hughes, M K, 1987 Dendroclimatology of *Pinus sylvestris* L. in the Scottish Highlands, in *Applications of tree-ring studies: Current research in dendrochronology and related subjects* (ed R G W Ward) (B.A.R), BAR international series, 333.

Hughes, M K, Schweingruber, F H, Cartwright, D, and Kelly, P M, 1984 July-August temperatures at Edinburgh between 1721 and 1975 from tree-ring density and width data, *Nature*, **308**, 341-4.

Hughes, P D M and Barber, K E, 2004 Constructing pathways to ombrotrophy in three raised bogs from Ireland and Cumbria, England, *The Holocene*, **14**, 65-77.

Hulme, M, Jenkins, G M, Lu, X, Turnpenny, J R, Mitchell, T D, Jones, R G, Lowe, J, Murphy, J M, Hassell, D, Booman, P, McDonald, R, and Hill, S, 2002 *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scienfific Report*, Norwich (Tyndall Centre, UEA).

Huntley, B, and Birks, H J B, 1983 *An atlas of past and present pollen maps of Europe: 0-13,000 Years Ago*, Cambridge (Cambridge University Press).

Huntley, B, Daniell, J R G, and Allen, J R M, 1997 Scottish vegetation history: the Highlands, *Botanical Journal of Scotland*, **49**, 163-76.

Hurrell, J W, 1995 Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation, *Science*, **269**, 676-9.

Hurrell, J W and Van Loon, H, 1997 Decadal Variations in climate associated with the North Atlantic Oscillation, *Climatic Change*, **36**, 301-26.

Ingram, H A P, 1982 Size and shape in raised mire ecosystems: a geophysical model, *Nature*, **297**, 300-3.

Ingram, H A P, 1983 Hydrology, in *Mires: Swamp, Bog, Fen and Moor* (ed A J P Gore), Amsterdam (Elsevier Scientific), Ecosystems of the World 4A

Ingram, H A P and Bragg, O M, 1984 The dipotelmic mire: some hydrological consequences reviewed, in *Proceedings of the Seventh International Peat Congress*, 220-34

Jacoby, G C and D'Arrigo, R D, 1995 Tree ring width and density evidence of climate and potential forest change in Alaska, *Global Biogeochemical Cycles*, **9**, 227-34.

Jalas, J, and Suominen, J, 1964 *Atlas Florae Europaeae: Distribution of Vascular Plants in Europe*, Cambridge (Cambridge University Press).

James, N D G, 1982 *The Forester's Companion*, Oxford (Basil Blackwell).

Joensuu, S, 1984 Säätekijöiden vaikutus oijettujen turvemaiden mäntyjen sädekasvuun (The influence of climatic factors on the radial growth of Scots pine in drained peatlands), *Suo*, **35**, 75-82.

Jones, P D, Briffa, K R, Barnett, T P, and Tett, S F B, 1998 High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures., *The Holocene*, **8**(4), 455-71.

Jones, P D, Jónsson, T, and Wheeler, D, 1997 Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland, *Int.J.Climatol.*, **17**, 1422-50.

Jones, P D and Lister, D, 2004 The Developement of Monthly Temperature Series for Scotland and Northern Ireland, *Int.J.Climatol.*, **24**, 569-90.

Jones, P D, Osborn, T J, and Briffa, K R, 2003 Pressure-based measures of the NAO: a comparison and assessment of changes in the strength of the NAO and in its influence on surface climate parameters, in *North Atlantic Oscillation* (eds J W Hurrell, Y Kushnir, G Ottersen, and M Visbeck), Washington (American Geophysical Union), 51-62.

Kaennel, M, and Schweingruber, F H, 1995 *Multilingual Glossary of Dendrochronology: Terms and definitions in English, German, French, Spanish, Italian, Portuguese and Russian*, 1-467 .Bern (Paul Haupt). Swiss Federal Institute for Forest, Snow and Landscape Research.

Kaunisto, S, Moilanen, M, and Issakainen, J, 1999 Effect of apatite and phlogopite application on the needle concentrations of *Pinus sylvestris* (L.) on drained pine mires, *Suo*, **50**(1), 15.

Kelly, P M, Jones.P., and Briffa, K R, 1997 Classifying the winds and weather, in *Climate of the British Isles: past, present and future* (eds M Hulme, and E Barrow), London and New York (Routledge), 153-69.

Kelly, P M, Munro, M A R, Hughes, M K, and Goodess, C M, 1989 Climate and signature years in west European oaks, *Nature*, **340**, 57-60.

Kilian, M R, Van de Plicht, J, and Van Geel, B, 1995 Dating raised bogs: New aspects of AMS ^{14}C wiggle matching, a reservoir effect and climate change, *Quaternary Science Reviews*, **14**(959), 966.

Kinloch, B B, Westfall, R D, and Forrest, G I, 1986 Caledonian Scots pine: origins and genetic structure, *New Phytologist*, **104**, 703-29.

Kolström, T, 2002 *External Factors forcing conifer growth variability at different frequencies during the Holocene in northern Europe and applications to ensure sustainable forest management*, International Scientific Cooperation Projects, Final Report, **Contract number: IC15-CT-98-0123**.

Kolström, T and Kellomaki, S, 1993 Tree survival in wildfires, *Silva Fennica*, **27**, 277-81.

Koski, V and Tallqvist, R, 1978 Results of long-time measurements of the quantity of flowering and seed crop of forest trees, *Act.For.Fenn.*, **66**, 1-106 (in Finnish, English summary).

Köstler, J N, Brückner, E, and Bibelriether, H, 1968 *Die Wurselm der Waldbäume*, Hamburg Berlin (in German) (Parey).

Krause, C and Eckstein, D, 1994 Dendrochronology of Roots, *Dendrochronologia*, **11**, 9-23.

Kullman, L, 1988 Short-term dynamic approchto tree limit and thermal climate: evidence from *Pinus sylvestris* L. in the Swedish Scandes, *Annales Botanici Fennici*, **25**, 219-27.

Kushnir, Y and Wallace, J M, 1989 Low-frequency variabilty in the Northern Hemisphere winter, *Journal of Atmosheric Science*, **46**, 3122-42.

Lageard, J G A, Chambers, F M, and Thomas, P A, 1999 Climatic significance of the marginalization of Scots pine (*Pinus sylvestris* L.) *c*. 2500 BC at White Moss, South Cheshire, UK, *Holocene*, **9**(3), 321-31.

Lageard, J G A, Thomas, P A, and Chambers, F M, 2000 Using fire scars and growth release in subfossil Scots pine to reconstruct prehistoric fires, *Palaeogeography Palaeoclimatology Palaeoecology*, **164**, 87-99.

Lamb, H H, 1964a *Quart.J.Roy.Meteor.Soc.*, **90**, 382.

Lamb, H H, 1964b Trees and climate history in Scotland, *Quart.J.Roy.Meteor.Soc.*, **90**, 382-94.

Lamb.P.J. and Peppler, R A, 1987 North Atlantic Oscillation: concept and application, *Bull.Amer.Meteor.Soc.*, **68**, 1217-25.

Landolt, W, 1977 *Ökologische Zeigerwerte zur Schweizer Flora*, 208 .Stiftung Rübel Zürich (Tchnischen Hochschule). Veröffentlichungen des Geobotanischen Institutes der Eidg.

Langdon, P G and Barber, K E, 2001 New Holocene tephras and a proxy climate record from a blanket mire in northern Skye, Scotland, *Journal of Quaternary Science*, **16**(8), 753-9.

Langdon, P G and Barber, K E, 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**, 259-74.

Langdon, P G and Barber, K E, 2004 Snapshots in time: precise correlatins of peat-based proxy climate records in Scotland using mid-Holocene tephras, *The Holocene*, **14**(1), 21-33.

Langdon, P G and Barber, K E, 2005 The climate of Scotland over the last 5000 years infered from multiproxy peatland records: intersite correlations and regional variability, *Journal of Quaternary Science*, **20**, 549-66.

Läänelaid, A, 1982 Radial increment of bog pines and climate changes, *Peatlands Ecosystems.Estonian Contributions to the Internatinal Biological Programme*, **9**, 135-7.

Leah, M D, Wells, C E, Appleby, C, and Huckerby, E, 1997 The Wetlands of Cheshire, in *North West Wetland Survey 4*, Cheshire County Council (Lancaster University Archaeology Unit).

Legg, C J, McHaffie, H, Amphlett, A, and Worrell, R, 2003 The status of wooded bogs at Abernethy, Strathspey, in *Restoring Natura Forest Habitats*, Munlochy (Highland Birchwoods), 12-6.

Lehtonen, H and Huttunen, P, 1997 History of forest fires in eastern Finland from the 15th Century AD: the possible effects of slash and burn cultivation, *The Holocene*, **7**, 223-8.

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, *Veget Hist Archaeobot*, **16**, 183-95.

Lewis, F J, 1905 The plant remains in the Scottish Peat Mosses, part I, *Trans.Roy.Soc.Edinb.*, **41**, 699-723.

Lewis, F J, 1906 The plant remains in the Scottish peat mosses. II. The Scottish Highlands, *Transactions of the Royal Society of Edinburgh*, **45**, 335-60.

Lewis, F J, 1908 The plant remains in the Scottish Peat Mosses III, *Transactions of the Royal Society of Edinburgh*, **46**, 33-70.

Lewis, F J, 1911 The plant remains in the Scottish Peat Mosses IV. The Scottish Highlands and Shetland, *Transactions of the Royal Society of Edinburgh*, **47**, 793-833.

Linder, S and Troeng, E, 1980 Photosynthsis and transpiration of 20-year-old Scots pine, *Ecological Bulletin, Stockholm*, **32**, 153-63.

Linderholm, H W, 1999 Climatic and anthropogenic influences in radial growth of Scots pine at Hanvedsmossen, a raised peat bog, in south central Sweden, *Geografiska Annaler*, **81 A**(1), 75-86.

Linderholm, H W, 2001 Climatic influence on Scots pine growth on dry and wet soils in the central Scandinavian Mountains, interpreted from tree-ring widths, *Silva Fennica*, **35**(4), 415-24.

Linderholm, H W, Moberg, A, and Grudd, H, 2002 Peatland pine as climate indicators? A regional comparison of the climate influence on Scots pine growth in Sweden, *Canadian Journal of Forest Research*, **32**, 1400-10.

Linderholm, H W, Solberg, B Ø, and Lindholm, M, 2003 Tree-ring records from central Fennoscandia: the relationship between tree grwoth and climate along a west-east transect, *The Holocene*, **13**(6), 887-95.

Lindholm, M., 1996 Reconstruction of the past climate from ring-width chronologies of Scots pine (*Pinus sylvestris* L.) at the northern forest limit in Fennoscandia, University of Joensuu, Facility of Natural Sciences, Department of Biology.

Lindsay, R A, 1995 *Bogs: the ecology, classification and conservation of ombrotrophic mires*, Edinburgh (Scottish Natural Heritage).

Lindsay, R A, Charman, D J, Everingham, R M, O'Reilly, M A, Palmer, T A, Rowell, T A, and Stroud, D A, 1988 *The Flow Country: the peatlands of Caithness and Sutherland*, Peterbrough (Nature Conservancy Council).

Lines, R and Mitchell, A F, 1964 Results of some older Scots pine provenance experiments, in *Report on Forest Research for the Year Ended March 1964*, London (HMSO), 171-94.

Low, A J, 1988 Scarification as an aid to natural regeneration in the Glen Tanar native pinewood, *Scottish Forestry*, **42**(1), 15-20.

Lowe, J J and NASP members, 1995 Palaeoclimate of the North Atlantic seaboards during the last Glacial/Interglacial transition, *Quaternary International*, **28**, 51-61.

Luckman, B H, 1993 Glacier Fluctuation and Tree-Ring Records for the Last Millenium in the Canadian Rockies, *Quaternary Science Reviews*, **12**.

Luckman, B H, 2007 Dendroclimatology, in *Encyclopedia of Quaternary Science* (ed S Elias), 465-75.

Luckman, B H, Briffa, K R, Jones, P D, and Schweingruber, F H, 1997 Tree-ring based reconstruction of summer temperatures at the Columbia Icefield, Alberta, Canada, *The Holocene*, **7**, 375-89.

Lundh, E, 1925 Produktionsundersökningar å avdikade marker inom Bjurfors kronopark, *Svenska Skogsvårdsföreningens tidskrift*, **23**, 315-48. (In Swedish).

Luterbacher, J, Schmutz, D, Gyalistras, E, Xoplaki, E, and Wanner, H, 1999 Reconstruction of monthly NAO and EU indicies back to AD 1675, *Geophys.Res.Lett.*, **26** , 2745-8.

Lührte von, A, 1991 Dendroökologische Untersuchungen an Kiefern und Eichen in den stadtnahen Berliner Forsten, in *Landschaftsentwicklung und Umweltforschung*, Berlin (Schriftenreihe des Fachbereichs Landschaftsentwicklung der TU), 186-. (In German).

Macias, M, Timonen, M, Kirchhefer, A J, Lindholm, M, Eronen, M, and Gutiérrez, M, 2004 Growth Variability of Scots Pine (*Pinus sylvestris*) along a West-East Gradient across Northern Fennoscandia: A Dendroclimatic Approch, *Arctic Antarctic and Alpine Research*, **36**(4), 565-74.

Mackay, E F, Redgate, N D, and Holmes, D W, 1999 *Wet Woods Life Project hydrological survey contract BAT/PA18/99/00/37. Monadh Mor*, Dingwall (Scottish Natural Heritage).

MacKay, J W B, 2004 Effect of burning on the mycorrhizal fungi of Scots pine *Pinus sylvestris* at Boat of Garten, Inverness-shire, Scotland, *Conservation Evidence*, **1**, 20-2.

MacKenzie, N A and Worrell, R, 1995 *A preliminary assessment of the ecology and status of ombrotrophic wooded bogs in Scotland*, Scottish Natural Heritage, Scottish Natural Heritage Report No, **40**.

Macklin, M G, Bonsall, C, Davies, F M, and Robinson, M R, 2000 Human-environment interations during the Holocene: new data and interpretations from the Oban area, Argyll, Scotland, *Holocene*, **10**(1), 109-21.

Macklin, M G, 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**, 937-43.

Magny, M, 1992 Holocene lake-level fluctuations in Jura and the northern subalpine ranges, France: regional pattern ands climatic implications, *Boreas*, **21**, 319-34.

Malcolm, D C and Cuttle, S P, 1983a The application of fertilizers to drained peat. 1. Nutrient losses in drainage, *Forestry*, **56**, 155-74.

Malcolm, D C and Cuttle, S P, 1983b The application of fertilizers to drained peat. 2. Uptake by vegetation and residual distribution in peat, *Forestry*, **56**, 175-83.

Malev, P L, 1955 *Carta Lesov SSSR 1:2,500,00*, Moscow.

Mannerkoski, H, 1985 *Effect of water table fluctuation on the ecology of peat soil*, Department of Peatland Forestry, University of Helsinki, **Publ. 7**.

Mannerkoski, H, 1991 Relation between tree roots and soil aeration on drained peatlands, in *Peat and Peatlands - diversification and innovation* (eds J K Jeglum, and R P Overend), Quebec (Canadian Society for Peat and Peatlands), 109-14.

Mason, W L, Edwards, C, and Hale, S E, 2004a Survival and early seeding growth of conifers with different shade tolerance in a Sitka spruce spacing trail and relationship to understorey light climate, *Silva Fennica*, **38**, 357-70.

Mason, W L, Hampson, A, and Edwards, C, 2004b *Managing the Pinewoods of Scotland*, Mason, W. L, Hampson, A., and Edwards, C. Edinburgh (Forestry Commission).

Mayes, J, 1994 Recent changes in the monthly distribution of weather types in the British Isles, *Weather*, **49**, 156-62.

McAulay, I R and Watts, W A, 1961 Dublin radiocarbon dates. I., *Radiocarbon*, **3**, 26-38.

McCarroll, D, Jalkanen, R, Hicks, S, Tuovinen, M, Gagen, M, Pawellek, F, Eckstein, D, Schmitt, U, Autio, J, and Heikkinen, O, 2003 Multiproxy dendroclimatology: a pilot study in northern Finland, *Holocene*, **13**, 829-38.

McCormac, F G and Buckland, P C, 2005 Faunal Change, in *Scotland After the Ice Age: Environment, Archaeology and History 8000 BC - AD 1000* (eds K J Edwards, and I B M Ralston), Edinburgh (Edinburgh University Press Ltd), 83-108.

McHaffie, H, Legg, C J, Worrell, R, and Amphlett, A, 2002 Scots Pine Growing of Forested Mires in Abernethy Forest, Strathspey, Scotland, *Botanical Journal of Scotland*, **54**(2), 209-19.

McNally, A, 1990 Dendrochronology of subfossil pine as evidence for environmental change, in *Ecology and Conservation of Irish Peatlands* (ed Royal Irish Academy), Dublin, 15-22.

McNally, A and Doyle, G T, 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**(6-7), 57-70.

McVean, D N, 1963a Ecology of Scots pine in the Scottish Highlands, *Journal of Ecology*, **51**(3), 671-86.

McVean, D N, 1963b Growth and mineral nutrition of Scots pine seedlings on some common peat types, *Journal of Ecology*, **51**, 657-70.

McVean, D N, and Ratcliffe, D A, 1962 *Plant communities of the Scottish Highlands*, London (HMSO).

Meeker, L D and Mayewski, P A, 2002 A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia, *The Holocene*, **12**, 257-66.

Mergen, F, 1984 Mechanical aspects of wind-breakage and wind firmness, *Journal of Forestry*, **52**, 119-25.

Metzger, A, 1893 Der Wind als massgebender Faktor für das Wachsthum der Bäume, *Mündener Forstl* , **3**, 35-86. (In German).

Michie, J G, 1901 *The Records of Invercauld 1547-1828*, Aberdeen (New Spalding Club).

Mickovski, S B and Enno, A R, 2003 Anchorage and asymmetry in the root system of *Pinus peuce*, *Silva Fennica*, **37**, 161-5.

Mighall, T M, Lageard, J G A, Chambers, F M, Field, M H, 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**(1), 95-109.

Mikola, P U, 1962 Temperature and tree growth near the northern timber line, in *Tree Growth* (ed T T Koslowski), New York (Ronald Press), 265-74.

Miles, J, 1988 Vegetation and soil change in the uplands, in *Ecological Change in the Uplands* (eds M B Usher, and D B A Thompson), London (Blackwell Scientific Publications), 57-70.

Miles, J and Kinnaird, J W, 1979 Grazing: with particular reference of birth, juniper and Scots pine in the Scottish Highlands, *Scottish Forestry*, **33**(4), 280-9.

Miller, H G and Cooper, J M, 1976 Tree growth and climatic cycles in the rain shadow of the Grampian mountains, *Nature*, **260**, 697-9.

Miller, K F, 1985 The influence of wind on commercial forestry in Scotland, in *Climatic Hazards in Scotland* (ed S J Harrison), Norwich (Geo Books), Proceedings of the Joint Royal Scottish Geographical Society and Meteorological Society Symposium, University of Stirling, June 1984, 41-9.

Mills, C M, 1988 Dendrochronology: the long and short of it, in *Science and archaeology* (eds E A Slater, and J O Tate), Glasgow, BAR Int Ser, **196**, 549-65.

Mitchell, F, 1986 *Shell Guide to Reading the Irish Landscape*, Dublin (Country House).

Mitchell, G F, 1956 Post-Boreal pollen diagrams from Irish raised bogs, *Proceedings of the Royal Irish Academy*, **57B**, 185-251.

Mitchell, G F, 1996 Vegetation history of the Killarney Valley: an overview, in *Central Kerry. Field guide no. 20* (eds C Delaney, and P Coxon), Dublin (Irish Association for Quaternary Studies), 23-6.

Mitchell, V, 1967 *An investigation of certain aspects of tree growth rates in relation to climate in the central Canadian boreal forest*, Department of Meteorology, University of Wisconsin, Technical report, **33**.

Moir, A K, 1994 *Dendrochronological Report on Farlary (Scotland)*, Geography Department, London Guildhall University.

Moir, A. K., 1996 Dendrochronological report on pine (*Pinus sylvestris* L.) stump samples: An initial investigation. In: Binney, H.A (1996*)* Holocene vegetation change and tree-line dynamics in the Scottish Highlands, Appendix 5.3, Unpublished PhD thesis, London Guildhall University.

Moore, P D, 1984 The classification of mires: an introduction, in *European Mires* (ed P D Moore), London (Academic Press), 1-10.

Morgan, R A, Litton, C D, and Salisbury, C R, 1987 Trackways and Tree Trunks: Dating Neolithic oaks in the British Isles, *Tree-ring Bulletin*, **47**, 61-9.

Morrison, D F, 1983 *Applied Linear Statistical Methods*, Englewood Cliffs, NJ (Prentice-Hall).

Morzukh, B J and Ruark, G A, 1991 Principal componants regression to mitigate the effects of multicollinearity, *Forest Science*, **37**(1), 191-9.

Moss, A E, 1940 Effect of wind-driven salt water, *Journal of Forestry*, **38**, 421-5.

Murray, A S and Clemmensen, L B, 2001 Luminescence dating of Holocene aeolian sand movement, Thy, Denmark, *Quaternary Science Reviews*, **20**, 751-4.

New, M, 1999 Representing twentieth-century space-time climate variability. Part I. Development of a 1961-90 mean monthly terrestrial climatology, *Journal of Climate*, **12**, 829-56.

Nicoll, B C and Ray, D, 1996 Adaptive growth of tree root systems in response to wind action and site conditions, *Tree Physiology*, **16**, 891-8.

Nixon, C J, 1996 A pilot study on the age structure and viability of the Mar Lodge pinewoods, *Scottish Forestry*, **48**(1), 22-7.

O'Brien, S R, Mayewski, P A, Meeker, L D, Meese, D A, Twickler, M S, and Whitlow, S I, 1995 Complexity of Holocene climate as reconstructed from a Greenland Ice core, *Science*, **270**, 1962-4.

O'Connell, M, Molloy, K, Holmes, J A, Jones, R, Leuenberger, M, Eicher, U, Schettler, G, Saarinen, T, McDermott, F, Van de Plicht, J, Chambers, F M, Hunt, J B, Daniell, J R G, Van Geel, B, Hass, J N, and Dalton.C., 2001 Evidence from the TIMECHS project for climatic instability during the early Holocene at the Atlantic fringe of Europe, *Terra nostra*, 159-61.

Oberhuber, W, 2001 The role of climate in the mortality of Scots pine (*Pinus sylvestris* L.) exposed to soil dryness, *Dendrochronologia*, **19**(1), 45-55.

Olsson, I U, 1986 A study of errors in ^{14}C dates of peats and sediment, *Radiocarbon*, **28**, 429-35.

Öquist, G, 1983 Effects of low temperature on photosythesis, *Plant, Cell and Environment*, **6**, 281-321.

P'javcenko, N I, 1960 O vzaimovlijanii materinskogo drevostoja i podrosta v sosnjake kustarnickovo-sfagnovom, *Tr.MOIP 3.*

Paavilainen, E, and Päivänen, J, 1995 *Peatland Forestry - Ecology and Principles*, Berlin (Springer-Verlag).

Parker, J, 1985 The hazards of Scotland's climate, in *Climatic Hazards in Scotland* (ed S J Harrison), Norwich (Geo Books), Proceedings of the Joint Royal Scottish Geographical Society and Royal Meteorological Society Symposium, University of Stirling, June 1984, 9-14.

Pasquill, F, and Smith, F B, 1983 *Atmospheric diffusion*, 3rdNew York (John Wiley and Sons).

Pears, N V, 1967 Present tree-lines of the Cairngorm Mountains, Scotland, *Journal of Ecology*, **55**, 815-29.

Pears, N V, 1968 Post-glacial tree-lines in the Cairngorm Mountains, Scotland, *Transactions of the Botanical.Society of Edinburgh*, **40**, 361-94.

Pears, N V, 1969 Post-glacial tree-lines of the Cairngorm Mountains, Scotland: some modifications based on radiocarbon dating, *Transactions of the Botanical.Society of Edinburgh*, **40**(5), 536-44.

Pears, N V, 1972 Interactive problems in the study of tree-line fluctuations, (University Collage of Wales), 31-45

Pears, N V, 1975 The growth rate of hill peats in Scotland, *Förhandlingar*, **97**, 265-70.

Pears, N V, 1988 Pine stumps, radiocarbon dates and stable isotope analysis in the Cairngorm mountains: some observations, *Review of Palaeobotany and Palynology*, **54**, 175-85.

Peet, R K, 1981 Forest vegetation of the Colorado Front Range: composition and dynamics, *Vegetatio*, **45**, 3-75.

Peglar, S, 1979 A radiocarbon dated pollen diagram from Loch of Winlass, Caithness, North East Scotland, *New Phytologist*, **82**, 245-63.

Pennington, W, 1975 A chronostratigraphic comparison of Late-Weichselian and Late Devensian subdivisions, illustrated by two radiocarbon dated profiles from western Britain, *Boreas*, **4**, 157-71.

Penttilä, T, 1991 Growth response of peatland stands to drainage in northern Finland, in *Peat and Peatlands - diversification and innovation* (eds J K Jeglum, and R P Overend), Quebec (Canadian Society for Peat and Peatlands), 70-7.

Perks, M P and Ennos, R A, 1999 Analysis of genetic variation for quantitative characters between and within four native populations of Scots Pine (*Pinus sylvestris*), *Botanical Journal of Scotland*, **51**(1), 103-10.

Pilcher, 1990 Sample preparation, cross-dating and measurement, in *Methods of dendrochronology. Applications in the environmental science.* (eds E R Cook, and L A Kairiukstis), Dordrecht (Kluwer), 40-51.

Pilcher, J R, 1991a Radiocarbon dating, in *Quaternary Dating Methods - a User's Guide* (eds P L Smart, and P D Frances), Cambridge (Quaternary Research Association), 16-36.

Pilcher, J R, 1991b Radiocarbon dating for the Quaternary scientist, *Quaternary Proceedings*, **1**, 27-33.

Pilcher, J R and Baillie, M G L, 1980 Eight modern oak chronologies from England and Scotland, *Tree-ring Bulletin*, **40**, 45-58.

Pilcher, J R, Baillie, M G L, Brown, D M, McCormac, F G, MacSweeney, P B, and McLawrence, A S, 1995 Dendrochronology of subfossil pine in the north of Ireland, *Journal of Ecology*, **83**(4), 665-71.

Pilcher, J R, Baillie, M G L, Schmidt, B, and Becker, B, 1984 A 7,272 year tree-ring chronology from W. Europe, *Nature*, **312**, 150-2.

Pilcher, J R and Hall, V A, 1992 Towards a tephrochronology for the Holocene of the north of Ireland, *The Holocene*, **2**, 255-9.

Pitkänen, A, Huttunen, P, Jungner, H, Meriläinen, J, and Tolonen, K, 2003 Holocene fire history of middle boreal pine forest sites in eastern Finland, *Annales Botanici Fennici*, **40**, 15-33.

Pitkänen, A, Tolonen, K, and Jungner, H, 2001 A basin based approch to the long-term history of forest fires as determined from peat strata, *Holocene*, **11** , 599-605.

Price, R J, 1983 *Scotland's Environment during the last 30,000 Years*, Edinburgh (Scottish Academic Press).

Printz, H, 1933 Granens og furuens fysiologi og geografiske utbredelse, *Nyt Mag.Naturvid*, **73**, 167-219.

Quine, C P, 2003 Wind as a disturbance agent and its implications for forest landscape patterns at Glen Affric, in *The potential of applied landscape ecology to forest design planning* (ed S Bell), Edinburgh (Forestry Commission), 55-62.

Quine, C P, Coutts, M P, Gardiner, B A, and Pyatt, D G, 1995 *Forests and Wind: Management to Minimise Damage*, London (HMSO). Forestry Commission Bulletin 114.

Rehfeldt, G E, Tchebakova, N M, Parfenova, Y I, Wykoff, W R, Kuzmina, N A, and Milyutin, L I, 2002 Intraspecific responses to climate in *Pinus sylvestris*, *Global Change Biology*, **8**, 912-29.

Reid, E, 2001 Landscape evolution and Holocene climate change in mountain areas of the northern Highlands, Scotland, Unpublished PhD thesis, University of Stirling.

Reid, E and Thomas, M F, 2006 A chronostratigraphy of mid- and late-Holocene slope evolution: Creagan a' Chaorainn, Northern Highlands, Scotland, *The Holocene*, **16**(3), 429-44.

Reimer, P J, Baillie, M G L, Bard, E, Bayliss, A, Beck.J.W., Bertrand, C J H, Blackwell, P G, Buck, C E, Burr, G S, Cutler, K B, Damon, P E, Edwards, R L, Fairbanks, R G, Friedrich, M, Guilderson, T P, Hogg, A G, Hughen, K A, Kromer, B, McCormac, G, Manning, S, Bronk Ramsey, C, Reimer, R W, Remmele, S, Southon, R J, Stuiver, M, Talamo, S, Taylor, F W, van der Plicht, J, and Weyhenmeyer, C E, 2004 IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP, *Radiocarbon*, **46**(3), 1029-58.

Rigg, G and Harrar, E, 1931 The root systems of trees growing in sphagnum, *American Journal of Botany*, **58**, 391-7.

Rigling, A, Bräker, O U, Schneiter, G, and Schweingruber, F H, 2002 Intra-annual tree-ring parameters indicating differences in drought stress of *Pinus sylvestris* forests within the Erico-Pinion in the Valais (Switzerland), *Plant Ecology*, **163**, 105-21.

Rigling, A, Brühlhart, H, Bräker, O U, Forster, T, and Schweingruber, F H, 2003 Effects of irrigation on diameter growth and vertical resin duct production in *Pinus sylvestris* L on dry sites in the central Alps, Switzerland, *Forest Ecology and Management*, **175**, 285-96.

Rind, D and Overpeck, J, 1993 Hypothesized causes of decade-to-century-scale climate variability: climate model results, *Quaternary Science Reviews*, **12**, 357-74.

Rodwell, J S, 1991 *Woodlands and Scrub*, Cambridge (Cambridge University Press). British Plant Communities.

Rogers, J C, 1984 The association between the North Altantic Oscillation and the Southern Oscillation in the Northern Hemisphere, *Monthly Weather Review*, **112**, 1999-2015.

Roy, M, 1997 The highlands and islands of Scotland, in *Regional climates of the British Isles* (eds D Wheeler, and J Mayes), 228-53.

Roy, V, Juel, J-C, and Plamondon, A P, 2000 Establishment, grwoth and survival of natural regeneration after clearcutting and drainage on forested wetlands, *Forest Ecology and Management*, **129**, 253-67.

Rushton, B S and Toner, A E, 1989 Wind damage to the leaves of sycamore (*Acer pseudoplantanus* L.) in coastal and non-coastal stands, *Forestry*, **62**, 67-88.

Sakai, A, and Larcher, W, 1987 *Frost survival in plants. Responses and adaptation to freezing stress*, Berlin Heidelberg New York (Springer).

Samuelsson, G, 1910 Scottish peat mosses: A contribution to the knowledge of the late-quaternary vegetation and climate of North Western Europe, *Bull.Geol.Inst.Upsala.*, **10**.

Sarkkola, S, Hökkä, H, and Penttilä, T, 2004 Natural development of stand structure in peatland Scots pine following drainage: Results based on long-term monitoring of permanent sample plots, *Silva Fennica*, **38**(4), 405-12.

Savva, Y V, Schweingruber, F H, and Vaganov, E A, 2001 Differences in tree-ring parameters of Scots pine provenances in response to annual conditions at a central Siberian location, in *International Conference Tree Rings and People. Davos, 22-26 September 2001*, (Swiss Federal Research Institute WSL), 246-7.

Schauffler, M, Jacobson, G L, Pugh, A L, and Norton, S A, 1996 Influence of vegetational structure on capture of salt and nutrient aerosols in a Maine peatland, *Ecological Applications*(6), 263-8.

Schimmel, J, 1993 *On fire, fire behaviour, fuel succession, and vegetation response to fire in the Swedish boreal forest*, SLU, Umeå (Department of Forest Vegetation Ecology). Dissertations in Forest Vegetation Ecology 5.

Schimmel, J and Granström, A, 1991 Skogsbrändernaoch vegetationen, *Skog & Forskning*, **4**, 39-46. (In Swedish).

Schmutz, D, Luterbacher, J, Gyalistras, E, Xoplaki, E, and Wanner, H, 2000 Can we trust proxy-based NAO index reconstructions, *Geophys.Res.Lett.*, **27**(8), 1135-8.

Schouten, M G C, Streefkerk, J G, and van der Molen, P C, 1992 Impact of climate change on bog ecosystems, with special reference to sub-oceanic raised bogs., *Wetland Ecology and Management*, **2**(1/2), 55-61.

Schove, D J and Frewer, A, 1961 *Scottish Forestry*, **15**, 63-71.

Schulman, E, 1941 Notes and Comment: Some propositions in tree-ring analysis, *Ecology*, **22**(2), 193-4.

Schulthess, J, 1990 *Der Einfluss von Entwässerung auf die Bewaldung eines Hochmoors*, 187-190 (In German) .Zurich, Switzerland (Diplomarbeit, Geographishes Institut Universität Zürich).

Schulz, M and Paul, A, 2002 Holocene Climate Variability on Centennial-to-Millennial Time Scales: 1. Climate Records from the North-Atlantic Realm, in *Climate Development and History of the North Atlantic Realm* (eds G Wefer, W H Berger, K-E Behre, and E Jansen), Berlin Heidelberg (Springer-Verlag), 41-54.

Schweingruber, F H, 1988 *Tree Rings: Basics and Applications of Dendrochronology*, Dordrecht, The Netherlands (Kluwer Academic Publishers).

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

Schweingruber, F H, Eckstein, D, Serre-Bachet, F, and Bräker, O U, 1990 Identification, presentation and interpretation of event years and pointer years in Dendrochronology, *Dendrochronologia*, **8**, 9-38.

Schweingruber, F H, Fritts, H C, Bräker, O U, and Schar, E, 1979 Dendroclimatic studies on conifers from central Europe and Great Britain, *Boreas*, **8**, 427-52.

Schweingruber, F H, Wehrli, U, and Allen-Rumo, K, 1991 Weiserjahre als Zeiger extreamer Standortseinflüsse, *Schweizerischen Zeitschrift für Forestwesen*, **142**, 33-52.

Scott, D, Welch, D, Thurlow, M, and Elston, D A, 2000 Regereration of *Pinus sylvestris* in a natural pinewood in NE Scotland following reduction in grazing by *Cervus elaphus*, *J.For.Ecol.Manage.*, **130**, 199-211.

Selten, F M, Haarsma, R J, and Opsteegh, J D, 1999 On the mechanism of North Atlantic decadal variability, *Journal of Climate*, **12**(7), 1956-73.

Seppälä, K, 1969 Post-drainage growth of Norway spruceand Scots pine on peat, *Acta Forestalia Fennica*, **93**, 89-. (in Finnish with English summary).

Sheppard, P R, Means, J E, and Lassoie, J P, 1988 Cross-dating cores as a nondestructive method for dating living, scarred trees, *Forest Science*, **34**, 781-9.

Shmida, A and Ellner, S, 1984 Coexistence of plant species with similar niches, *Vegetatio*, **58**, 29-55.

Shore, J S, Bartley, D D, and Harkness, D D, 1995 Problems encountered with the ^{14}C dating of peat, *Quaternary Science Reviews*, **14**, 373-83.

Sillasoo, Ü, Mauquoy, D, Blaauw, M, Daniell, J R G, Toms, P, Newberry, J, Chambers, F M, and Karofeldt, E, 2007 Plant macro-fossils and peat humification at Männikjärve bog as indicators of Late Holocene climate chages in Estonia, *Boreas*, **36**, 20-37.

Sirén, G, 1961 Skogsgränstallen som indikator för klimatfluktuationerna i norra Fennoskandien under historisk tid, *Communicationes Instituti Forestalis Fenniae*, **54**(2), 3-65. (In Swedish).

Smith, H G and Pilcher, J R, 1973 Radiocarbon dates and vegetational history of the British Isles, *New Phytologist*, **72**, 903-14.

Smith, R, 1900 On seed dispersal of *Pinus sylvestris* and *Betula alba*, *Scot.Nat.*, **33**, 43-6.

Spencer, D A, 1964 Porcupine Population fluctuations in Past Centuries revealed by Dendrochronology, *The Journal of Applied Ecology*, **1**(1), 127-49.

Speranza, A, van der Plicht, J, and Van Geel, B, 2000 Improving the time control of the Subboreal/Subatlantic transition in a Czech peat sequence by ^{14}C wiggle-matching, *Quaternary Science Reviews*, **19**, 1589-604.

Stepanek, P, 2006a *AnClim - software for time series analysis (for Windows)*, Dept. of Geography, Fac. of Natural Sciences, Masaryk University, Brno.

Stepanek, P, 2006b *ProClimDB - software for processing climatological datasets.*, CHMI, regional office Brno.

Steven, A M, and Carter, A H C, 1959 *The Native Pinewoods of Scotland*, Edinburgh & London (Oliver and Boyd).

Stokes, A, Nicoll, B C, Coutts, M P, and Fitter, A H, 1995 Responses of yound trees to wind and shading: effects on root architecture, *Journal of Experimental Botany*, **46**, 21-6.

Stokes, M A, and Smiley, T L, 1968 *An Introduction to Tree Ring Dating*, Chicago (University of Chicago Press).

Stroud, D A, Reed, T M, Pienkowski, M W, and Lindsay, R A, 1987 *Birds, Bogs and Forestry*, Peterborough (Nature Conservancy Council).

Stuiver, M, Grootes, P M, and Braziunas, T F, 1995 The GISP2 and ^{18}O climate record of the past 16,500 years and the role of the sun, ocean and volcanoes, *Quaternary Research*, **44**, 341-54.

Suffling, R, 1992 Climate change and boreal forest fires in Fennoscandia and Central Canada, in *Greenhouse impact on cold-climate ecosystems and landscapes* (eds M Boer, and E Koster), Catena supplement 22, 111-32.

Swain, C., 1987 Dendroclimatology of *Pinus sylvestris* L. in the British Isles, Unpublished PhD thesis, University of Liverpool.

Switsur, V R and West, R G, 1975 University of Cambridge natural radiocarbon measurements XIII, *Radiocarbon*, **17**, 35-51.

Tallis, J H and Switsur, V R, 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.

Tate, H., 1997 A dendrochronological study from Coventry, West Midlands, Unpublished BSc thesis, Coventry University.

Tegelmark, D O, 1998 Site factors as multivariate predictors of the success of natural regeneration in Scots pine forests, *Forest Ecology and Management*, **109**, 231-9.

Telewski, F W, 1989 Structure and function of flexure wood in *Abies fraseri*, *Tree Physiology*, **5**(113), 122.

Telewski, F W, 1990 Growth, wood density, and ethylene production in response to mechanical perturbation in *Pinus taeda*, *Canadian Journal of Forest Research*, **20**, 1277-82.

Telewski, F W, 1995 Wind-induced physiological and developmental response in trees, in *Wind and Trees* (eds M P Coutts, and J Grace), Cambridge, 237-63.

Telewski, F W and Jaffe, M J, 1981 Thigmomorphogenesis: changes in the morphology, and chemical composition induced by mechanical perturbation of a 6-month-old *Pinus taeda* seedlings, *Canadian Journal of Forest Research*, **11**, 380-7.

Telewski, F W and Lynch, A M, 1991 Measuring growth and development of stems, in *Techniques and Approaches in Forest Tree Ecophysiology* (eds J P Lassoie, and S Jiang), Boca Raton (CRC Press)

Telford, M. B., 1977 Glenveagh National Park: the past and present vegetation, Unpublished PhD thesis, University of Dublin (Trinity Collage).

Tessier, L, 1986 Approche dendroclimatologique de l'écologie de *Pinus sylvestris* L. et *Quercus pubescens* Willd. dans le sud-est de la France, *Acta Oecologica*, **7**(4), 339-55. (In French).

Tessier, L, Guibal, F, and Schweingruber, F H, 1997 Research strategies in dendroecology and dendroclimatology in mountain environments, *Climatic Change*, **36**(3-4), 499-517.

Tipping, R, 1996 Microscopic charcoal records, inferred human activity and climate change in the mesolithic of northernmost Scotland, in *The Early Pre-history of Scotland* (eds A Pollard, and A Morrison), Edinburgh (Edinburgh University Press), 39-61.

Tipping, R, 2007 Storminess as an explanation for the decline of pine woodland ca. 7,400 years ago at Loch Tulla, western Scotland, *Veget Hist Archaeobot.*

Tipping, R, Ashmore, P, Davies, A, Haggart, B A, Moir, A K, Newton, A, Sands, R, Skinner, T, and Tisdall, E W, 2007a Peat, pine stumps and people: interactions behind climate, vegetation change and human activity in wetland archaeology at Loch Farlary, northern Scotland, in *Archaeology from the Wetlands: recent perspectives* (eds J Barber, C Clark, M Cressey, A Crone, A Hale, J Henderson, R Housley, R Sands, and A Sheridan), Edinburgh (Society of Antiqaries of Scotland), WARP Occasional Paper 18, 157-64.

Tipping, R, Ashmore, P, Davies, A, Haggart, B A, Moir, A K, Newton, A, Sands, R, Skinner, T, and Tisdall, E W, 2007b Prehistoric *Pinus* woodland dynamics in an upland landscape in northern Scotland: the role of climate change and human impact, *Veget Hist Archaeobot*

Tipping, R, Davies, A, and Tisdall, E W, 2006 Long-term woodland dynamics in West Glen Affric, northern Scotland, *Forestry*, **79**, 351-9.

Tisdall, E W, 2003 Loch Coulavie: stratigraphic data on Holocene lake level and proxy precipitation change, in *The Quaternary of Glen Affric and Kintail. Field Guide* (ed R M Tipping), London (Quaternary Research Association), 55-62.

Tranquillini, W, 1979 *Physiological ecology of the alpine treeline*, Berlin (Springer).

Trottier, F, 1991 Draining wooded peatlands: expected growth gains, in *Peat and Peatlands - diversification and innovation* (eds J K Jeglum, and R P Overend), Quebec (Canadian Society for Peat and Peatlands), 78-82.

Tucker, G F, Hinckley, T M, Leverenz, J W, and Jiang, S, 1987 Adjustments in foliar morphology in the acclimation of understory Pacific silver fir following clearcutting, *Forest Ecology and Management*, **21**, 249-62.

Tuittila, E-S, Väliranta, M, Laine, A, and Korhola, A, 2007 Quantifying patterns and controls of mire vegetation succession in a southern boreal bog using a combination of partical ordinations, *Journal of Vegetation Science*

Turney, C S M, Baillie, M, Palmer, J G, and Brown, D M, 2006 Holocene climatic change and past Irish societal response, *Journal of Archaeological Science*, **33**, 34-8.

Turney, C S M, Baillie, M G L, Clemens, S, Brown, D M, Palmer, J G, Pilcher, J R, Reimer, P J, and Leuschner, H-H, 2005 Testing solar forcing of pervasive Holocene climate cycles, *Journal of Quaternary Science*, **20**, 511-8.

Turunen, J, Pitkänen, A, Tahvanainnen, T, and Tolonen, K, 2001 Carbon accumulation in West Siberian mires, Russia, *Global Biogeochemical Cycles*, **15**, 285-96.

Tyers, I, 1999 *Dendro for Windows Program Guide 2nd Edition*, ARCUS Rep, **500**.

Vaganov, E A and Kachaev, A V, 1992 Dendroclimatic analysis of the growth of pine in forest-bog phytocenoses of Tomsk Oblast, *Lesovedenie*, **6**, 3-10.

Van Geel, B and Mook, W G, 1989 High resolution ^{14}C dating of organic deposits using natural atmospheric ^{14}C variations, *Radiocarbon*, **31**, 151-5.

Van Loon, H and Rogers, J C, 1978 The seesaw in winter temperatures between Greenland and Northern Europe. Part 1 General description, *Monthly Weather Review*, **106**, 296-310.

VanHoorne, R and van Strydonck, M, 1976 Antwerp University radiocarbon dates I, *Radiocarbon*, **18**, 151-60.

VanHoorne, R and van Strydonck, M, 1977 Antwerp University radiocarbon dates II, *Radiocarbon*, **19**, 383-8.

VanHoorne, R, van Strydonck, M, and Dubois, A D, 1978 Antwerp University radiocarbon dates III, *Radiocarbon*, **20**, 192-9.

Vasari, Y, 1968 Late and Post-glacial macrophytic vegetation in the lochs of northern Scotland, *Acta Botanica Fennica*, **80**, 1-120.

Vazquez, E G, 1947 *Silvicultura*, Dossat (South Africa).

Väliranta, M, Korhola, A, Seppä, H, Tuittila, E-S, Sarmaja-Korjonen, K, Laine, J, and Alm, J, 2007 High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: a quantitive approach, *The Holocene*, **17**(8), 1093-107.

Vila, B, Torre, F, Guibal, F, and Martin, J-L, 2003 Growth change of young *Picea sitchensis* in response to deer browsing, *Forest Ecology and Management*, **180**, 413-24.

Walker, G T, 1924 Correlations in seasonal variations of weather IX, *Mem.Ind.Meteorol.Dept.*, **24**, 275-332.

Walker, M J C, 1984 A pollen diagram from St Kilda, Outer Hebridies, Scotland, *New Phytologist*, **97**, 99-113.

Ward, R G W, Haggert, B A, and Bridge, M C, 1987 Dendrochronological studies of bog pine from the Rannoch Moor Area, Western Scotland, in *Applications of Tree-Ring Studies* (ed R G W Ward), Oxford (BAR), British Archaeological Reports, International Series, 333, 215-25.

Warren, W G, 1980 On removing the growth trend from dendrochronological data, *Tree-ring Bulletin*, **40**, 35-44.

Watson, A, 1983 Eighteenth century deer numbers and pine regeneration near Braemar, Scotland, *Biol.Conserv.*, **25**, 289-305.

Wells, C E, 2002 *A survey of the peat stratigraphy of seven 'bog woodland' sites in Scotland*.

Westman, C J and Laiho, R, 2003 Nutrient Dynamics of Drained Peatland Forests, *Biogeochemistry*, **63**(3), 269-98.

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

White, J E J, 1998 *Estimating the age of large and veteran trees in Britain*, Forestry Commission, Information Note, **250**.

Wigley, T M L, Briffa, K R, and Jones, P D, 1984 On the average value of correlated time-series, with applications in Dendroclimatology and Hydrometeorolgy, *Journal of Climate and Applied Meteorology*, **23**(2), 201-13.

Wilkins, D A, 1984 The Flandrian woods of Lewis (Scotland), *Journal of Ecology*, **72**, 251-8.

Williams, W., 1977 The Flandrian vegetational history of the Isle of Skye and the Morar Peninsula, Unpublished PhD thesis, University of Cambridge.

Wilmking, M, D'Arrigo, R D, Jacoby, G C, and Juday, G P, 2005 Increased temperature sensitivity and divergent growth trends in circumpolar boreal forests, *Geophysical Research Letters*, **32**.

Wilson, B F, 1975 Distribution of secondary thickening in tree root systems, in *The development and function of roots* (eds J G Torrey, and D T Clarkson), London (Academic Press), 197-219.

Wilson, P, McGourty, J, and Bateman, M D, 2004 Mid- to late-Holocene coastal dune event stratigraphy for the north coast of Northern ireland, *The Holocene*, **14**(3), 406-16.

Wilson, R J S and Elling, W, 2004 Temporal instabilities of tree-growth/climate reponse in the Lower Bavarian Forest Region: Implications for dendroclimatic reconstruction, *Trees: Structure and Function*, **18**(1), 19-28.

Witak, M, Wachnicka, A, Kuijpers, A, Troelstra, S, Prins, M A, and Witkowski, A, 2005 Holocene North Atlantic surface circulation and climate variability: evidence from diatom records, *The Holocene*, **15**, 85-96.

Worrell, R, 1990 *Factors affecting natural regeneration of conifers in upland Britain: a literature review*, Forest Research, Forest Reseach Internal report.

Yu, G and Harrison, S P, 1995 Holocene changes in atmospheric circulation patterns as shown by lake status changes in northern Europe, *Boreas*, **24**, 260-8.

Zackrisson, O, 1977 Influence of forest fires on the north Swedish boreal forest, *Oikos*, **29**(1), 22-32.

Zackrisson, O, 1980 *Forest fire history: ecological significance and dating problems in the north Swedish boreal forest*, US Department of Agriculture, USDA Forest Services General Technical Report, **RM-81**.

Zackrisson, O and Östlund, L, 1991 Branden formade skoglandskapets mosaik, *Skog & Forskning*, **4**, 13-21 (In Swedish).

Zetterberg, P, Eronen, M, and Briffa, K R, 1994 Evidence on climatic variability and prehistoric activities between 165B.C and A. D. 1400 derived from subfossil Scots pine (*Pinus sylvestris* L.) found in a lake in Utsjoki, northernmost Finland, *Bull.Geol.Soc Finland*, **66**(2), 107-24.

7 APPENDICES

7.1 Appendix I: Radiocarbon dates for subfossil pine from peat substrate in the British Isles

Sources: (a) Birks (1975); (b) Pears (1972); (c) Bridge *et al.* (1990); (d) Dauchot-Dehan *et al.* (1981); (e) Dubois & Ferguson (1985); (f) VanHoorne and Van Strydonck (1977); (g) VanHoorne and Van Strydonck (1976); (h) VanHoorne *et al.* (1978); (i) Daniell (1997); (j) Switsur and West (1975); (k) Tipping (2007a); (l) Lamb (Lamb 1964a); (m) Wilkins (1984); (n) Gear (1991); (o) Dickson (1988); (p) Mighall (2004); (q) Pilcher (1995); (r) Smith and Pilcher (1973); (s) Godwin and Willis (1960); (t) Caulfield *et al.* (1998); (u) Tallis and Switsur (1983); (v) Telford (1977); (w) Mitchell (1996); (x) Mitchell (1956); (y) McAulay and Watts (1961); (z) McNally (1990); (aa) Lageard *et al.* (1999). See section 2.5 for details on calibration.

Location	**Lab code**	**Date (uncalibrated yr BP)**	**±S.D.**	**Longitude**	**Latitude**	**Source**
Clatteringshaws, Scotland	Q-878	5080	100	-4.29	55.07	a
Loch Dungeon, Scotland	Q-876	7165	180	-4.32	55.13	a
Cooran Lane, Scotland	Q-875	6564	120	-4.39	55.13	a
Cooran Lane, Scotland	Q-871	7471	120	-4.39	55.13	a
Barns of Bynack, Scotland	GAK-2540	5110	150	-3.53	56.23	b
Clashgour, Rannoch, Scotland	SRR-3370	5735	50	-4.86	56.52	c
Clashgour, Rannoch, Scotland	SRR-3365	5065	45	-4.85	56.54	c
Clashgour, Rannoch, Scotland	SRR-3364	5900	45	-4.85	56.54	c
Clashgour, Rannoch, Scotland	SRR-3367	6040	50	-4.85	56.54	c
Clashgour, Rannoch, Scotland	SRR-3369	6095	40	-4.85	56.54	c
Clashgour, Rannoch, Scotland	SRR-3362	6160	50	-4.85	56.54	c
Clashgour, Rannoch, Scotland	SRR-3363	6835	40	-4.85	56.54	c
Coire Seilich, Rannoch, Scotland	SRR-3368	1360	50	-4.85	56.54	c
Coire Seilich, Rannoch, Scotland	SRR-3377	4000	40	-4.70	56.58	c
Coire Seilich, Rannoch, Scotland	SRR-3378	4290	40	-4.70	56.58	c
Coire Seilich, Rannoch, Scotland	SRR-3373	4540	50	-4.70	56.58	c
Coire Seilich, Rannoch, Scotland	SRR-3375	5110	45	-4.70	56.58	c
Coire Seilich, Rannoch, Scotland	SRR-3376	5060	40	-4.70	56.58	c
Coire Seilich, Rannoch, Scotland	SRR-3374	5130	45	-4.70	56.58	c
Coire Seilich, Rannoch, Scotland	SRR-3371	5575	50	-4.70	56.58	c
Coire Seilich, Rannoch, Scotland	SRR-3372	6605	50	-4.70	56.58	c
Gorton, Rannoch, Scotland	SRR-3381	4405	45	-4.62	56.59	c
Gorton, Rannoch, Scotland	SRR-3383	4560	45	-4.62	56.59	c
Gorton, Rannoch, Scotland	SRR-3380	4765	50	-4.62	56.59	c
Gorton, Rannoch, Scotland	SRR-3384	5160	40	-4.62	56.59	c
Gorton, Rannoch, Scotland	SRR-3385	5190	50	-4.62	56.59	c
Gorton, Rannoch, Scotland	SRR-3382	5495	45	-4.62	56.59	c
Gorton, Rannoch, Scotland	SRR-3379	6220	50	-4.62	56.59	c
Carn Mor, Scotland	GAK-2003	2880	220	-3.60	57.00	a, b
Carn Mor, Scotland	GAK-2006	6700	300	-3.60	57.00	a, b
Sgor Mor, Scotland	BIRM-134	4130	110	-3.64	57.00	a, b
Sgor Mor, Scotland	GAK-2004	4140	220	-3.64	57.00	a, b
Cairngorm Est, Scotland	IRPA-358	5070	260	-4.08	57.06	d
Cairngorm Est, Scotland	IRPA-592	1780	60	-4.08	57.06	e
Cairngorm Est, Scotland	IRPA-595	4760	80	-4.08	57.06	e
Cairngorm Est, Scotland	IRPA-602	4660	70	-4.08	57.06	e
Loch Einich, Scotland	K-1418	5970	120	-3.78	57.08	a

Location	Lab code	Date (uncalibrated yr BP)	±S.D.	Longitude	Latitude	Source
Cairngorm Est, Scotland	ANTW-202	6620	68	-3.70	57.11	f
Cairngorm Est, Scotland	ANTW-203	7060	97	-3.70	57.11	f
Cairngorm Est, Scotland	ANTW-199	5140	69	-3.70	57.12	f
Cairngorm Est, Scotland	ANTW-177	4470	105	-3.67	57.12	f
Cairngorm Est, Scotland	?	6400	98	-3.67	57.12	f
Cairngorm Est, Scotland	ANTW-91	7380	150	-3.69	57.12	g
Jean's Hut, Scotland	GAK-2005	4630	210	-3.66	57.13	a
Cairngorm Est, Scotland	ANTW-236	5690	60	-3.70	57.13	h
Cairngorm Est, Scotland	ANTW-221	4150	70	-3.70	57.13	h
Cairngorm Est, Scotland	ANTW-259	3940	95	-3.70	57.13	h
Cairngorm Est, Scotland	ANTW-269	4450	140	-3.70	57.13	h
Cairngorm Est, Scotland	?	1190	55	-3.69	57.13	h
Cairngorm Est, Scotland	ANTW-220	6210	120	-3.69	57.13	h
Cairngorm Est, Scotland	ANTW-219	5990	63	-3.69	57.13	f
Cairngorm Est, Scotland	ANT-218	5790	80	-3.69	57.13	f
Cairngorm Est, Scotland	ANTW-192	3780	60	-3.65	57.13	f
Cairngorm Est, Scotland	ANTW-107	4170	140	-3.65	57.14	g
Cairngorm Est, Scotland	ANTW-277	3940	60	-3.65	57.14	h
Cairngorm Est, Scotland	IRPA-365	4350	240	-3.65	57.14	d
Cairngorm Est, Scotland	ANTW-193	3320	55	-3.65	57.14	f
Cairngorm Est, Scotland	ANTW-194	4090	62	-3.65	57.14	f
Cairngorm Est, Scotland	ANTW-200	4410	54	-3.65	57.14	h
Cairngorm Est, Scotland	ANTW-171	3410	80	-3.65	57.14	f
Cairngorm Est, Scotland	ANTW-278	2670	65	-3.67	57.15	h
Cairngorm Est, Scotland	IRPA-360	4140	210	-3.65	57.15	d
Cairngorm Est, Scotland	?	4200	230	-3.65	57.15	d
Meall A'Bhuachaille, Scotland	GAK-2541	4400	120	-3.67	57.18	b
Meall A'Bhuachaille, Scotland	GAK-2539	6150	150	-3.67	57.18	b
Allt na Feithe S, Scotland	K-1419	6960	130	-3.91	57.31	a
Cairngorm Est, Scotland	IRPA-364	4660	240	-3.68	57.71	d
Loch Glascarnoch, Scotland	SRR-5799	5975	40	-4.87	57.72	i
Fain, Scotland	SRR-5798	4165	45	-5.09	57.74	i
Beinn Dearg, Scotland	Q-1153	4320	80	-4.93	57.75	a, j
Corie Bog, Scotland	Q-887	6980	100	-4.37	57.84	a
Knockanrock, Scotland	SRR-5800	4365	45	-5.09	58.01	i
Loch Farlary, Scotland	AA-53150	4020	40	-4.08	58.02	k
Loch Farlary, Scotland	AA-53143	4185	40	-4.08	58.02	k
Loch Farlary, Scotland	AA-53145	4195	40	-4.08	58.02	k
Loch Farlary, Scotland	AA-53147	4175	40	-4.08	58.02	k
Loch Farlary, Scotland	AA-53149	4175	40	-4.08	58.02	k
Loch Farlary, Scotland	GU-3964	4140	50	-4.08	58.02	k
Loch Farlary, Scotland	AA-53148	4260	45	-4.08	58.02	k
Loch Farlary, Scotland	AA-53144	4395	50	-4.08	58.02	k
Loch Farlary, Scotland	AA-53146	5630	55	-4.08	58.02	k
Rogart, Scotland	Q-1156	3976	100	-4.14	58.03	a
Badentarbat Lodge B, Scotland	NPL-14	4220	105	-5.37	58.04	a, l, i
Badentarbat Lodge A, Scotland	NPL-13	4420	102	-5.37	58.04	a, l, i
Inverpolly, Scotland	Q-1031	4674	60	-5.22	58.04	a
Airde, Loch Shin, Scotland	SRR-5795	4070	45	-4.71	58.05	i
L. Strandavat, Scotland	Q-2288/9	4740	50	-6.65	58.08	m

Location	Lab code	Date (uncalibrated yr BP)	±S.D.	Longitude	Latitude	Source
Loch Shin, Scotland	SRR-5810	4710	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5803	4895	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5805	4560	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5809	4665	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5811	4685	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5804	4680	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5808	4595	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5812	4570	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5806	4415	45	-4.59	58.14	i
Loch Shin, Scotland	SRR-5807	4380	45	-4.59	58.14	i
Loch Vatachan, Scotland	SRR-5814	4570	45	-5.36	58.03	i
Loch Raithair, Scotland	UBA-8470	4409	32	-3.94	58.29	Author
Badanloch, Scotland	SRR-3566	4405	50	-4.07	58.27	i
Badanloch, Scotland	SRR-3567	4370	50	-4.07	58.27	i
Strath Kanaird, Scotland	UBA-8469	4335	31	-5.12	57.97	Author
Scotland	SRR-3573	4395	50	-4.72	58.14	n
Little L. Roag, Scotland	BIRM1093	4870	100	-6.89	58.14	m
Inchnadamph, Scotland	Q-1155	4163	80	-4.98	58.14	a
L. Thota Bridein, Scotland	BIRM1094	4390	100	-6.53	58.16	m
Abhainn Dhubh, Scotland	BIRM1092	4740	120	-6.71	58.18	m
Scotland	SRR-3566	4405	50	-4.22	58.24	n
Scotland	SRR-3567	4370	50	-4.22	58.24	n
Isle of Lewis, Scotland	BIRM1058	3910	70	-6.61	58.27	m
Scotland	SRR-3560	4220	65	-4.39	58.33	n
Scotland	SRR-3559	4390	65	-4.39	58.33	n
Scotland	SRR-3501	4225	60	-4.22	58.33	n
Scotland	SRR-3561	3955	55	-4.05	58.33	n
Scotland	SRR-3562	4335	50	-4.05	58.33	n
Scotland	SRR-3565	3815	50	-3.88	58.33	n
Scotland	SRR-3564	3985	50	-3.88	58.33	n
Laxford Bridge, Scotland	SRR-5801	3935	45	-5.03	58.37	i
Lochstrathy, Scotland	SRR-3576	4155	50	-4.06	58.41	i, n
Lochstrathy, Scotland	SRR-3575	4255	50	-4.06	58.41	i, n
Lochstrathy, Scotland	SRR-3578	4300	65	-4.06	58.41	i, n
Lochstrathy, Scotland	SRR-3574	4385	50	-4.06	58.41	i, n
Lochstrathy, Scotland	SRR-3577	4360	50	-4.06	58.41	i, n
Scotland	SRR-3558	3945	55	-4.40	58.42	n
Scotland	SRR-3557	4295	65	-4.40	58.42	n
Scotland	SRR-3571	3865	50	-3.71	58.43	n
Loch Eriboll, Scotland	SRR-5797	4460	45	-4.75	58.44	i
Strath Dionard, Scotland	SRR-5796	4270	45	-4.85	58.48	i
Scotland	SRR-3568	4275	50	-5.09	58.49	n
Scotland	SRR-3555	3825	50	-4.58	58.50	n
Scotland	SRR-3556	4045	65	-4.58	58.50	n
A'Mhoine, Scotland	SRR-5802	4530	45	-4.50	58.50	i
A'Mhoine, Eriboll, Scotland	Q-1121	4393	50	-4.60	58.51	a
Scotland	SRR-3569	4050	60	-4.23	58.51	n
Loch Sian, Scotland	SRR-5813	4360	45	-4.70	58.51	i
Corire Bog, Scotland	Q-887	6980	100	-4.37	57.84	a
Kinlochewe, Scotland	Q-1150	4447	100	-5.2992	57.604	a

Location	Lab code	Date (uncalibrated yr BP)	±S.D.	Longitude	Latitude	Source
Kinlochewe, Scotland	Q-1151	4671	80	-5.2992	57.604	a
Rannoch Moor, Scotland	Q-1157	4395	90	-4.70	56.58	a
Rannoch Moor, Scotland	Q-1158	6139	110	-4.70	56.58	a
Drumbow, Scotland	GU-113	2940	55	-3.87	55.90	o
Cadogan's Bog, Ireland	AA36254	4485	70	-9.49463	51.572	p
Cadogan's Bog, Ireland	SRR-6544	4815	40	-9.49463	51.572	p
Cadogan's Bog, Ireland	SRR-6545	4170	50	-9.49463	51.572	p
Cadogan's Bog, Ireland	SRR-6546	6610	45	-9.49463	51.572	p
Cadogan's Bog, Ireland	B-114958	6410	70	-9.49463	51.572	p
Cadogan's Bog, Ireland	SRR-6547	4805	45	-9.49463	51.572	p
Cadogan's Bog, Ireland	SRR-6548	4580	40	-9.49463	51.572	p
Sluggan Bog, N. Ireland	UB-3565	7234	25	-6.30	54.77	q
Sluggan Bog, N. Ireland	UB-3564	6709	25	-6.30	54.77	q
Derrycrow, N. Ireland	UB-528	4630	60	-6.45	54.50	r
Fallahogy, N. Ireland	UB-621	7245	100	-6.57	54.90	r
Sharvogues, N. Ireland	UB-623	3795	75	-6.28	54.80	r
Sharvogues, N. Ireland	UB-624	4015	45	-6.28	54.80	r
Sharvogues, N. Ireland	UB-529	4670	45	-6.28	54.80	r
Sharvogues, N. Ireland	UB-611	4855	80	-6.28	54.80	r
Sluggan Bog, N. Ireland	UB-459	7095	115	-6.30	54.77	r
Sluggan Bog, N. Ireland	UB-460	6615	95	-6.30	54.77	r
Sluggan Bog, N. Ireland	UB-610	6855	95	-6.30	54.77	r
Sluggan Bog, N. Ireland	UB-622	7005	65	-6.30	54.77	r
Altnahinch, N. Ireland	UB-530	6255	100	-6.25	55.05	r
Altnahinch, N. Ireland	UB-612	4510	80	-6.25	55.05	r
Altnahinch, N. Ireland	UB-609	5500	85	-6.25	55.05	r
Whixall Moss, Shropshire, England	Q-383	2307	110	-2.10	52.92	s
Llyn Teifi, Cardiganshire, Wales	Q-394	5261	120	-3.12	52.28	s
Ceide Fields, Ireland	UCD-C45	4450	60	-9.46	54.30	t
Ceide Fields, Ireland	UCD-C51	4500	60	-9.46	54.30	t
Ceide Fields, Ireland	UCD-C57	4420	50	-9.47	54.30	t
Ceide Fields, Ireland	UCD-C42	4530	60	-9.44	54.30	t
Ceide Fields, Ireland	UCD-C44	5370	70	-9.44	54.30	t
Ceide Fields, Ireland	UCD-C21	4490	60	-9.42	54.29	t
Ceide Fields, Ireland	UCD-C23	4540	60	-9.43	54.28	t
Ceide Fields, Ireland	UCD-C28	4230	60	-9.43	54.28	t
Ceide Fields, Ireland	UCD-C29	4510	50	-9.43	54.28	t
Ceide Fields, Ireland	UCD-C34	3950	60	-9.42	54.28	t
Ceide Fields, Ireland	UCD-C37	4500	50	-9.42	54.28	t
Ceide Fields, Ireland	UCD-C22	4210	60	-9.40	54.26	t
Ceide Fields, Ireland	UCD-C27	4170	50	-9.39	54.26	t
Ceide Fields, Ireland	UCD-C30	4190	50	-9.40	54.26	t
Ceide Fields, Ireland	UCD-C33	4100	60	-9.40	54.26	t
Belderrig, Ireland	UCD-C04	4480	60	-9.54	54.31	t
Belderrig, Ireland	UCD-C11	4010	60	-9.53	54.31	t
Belderrig, Ireland	UCD-C14	4310	70	-9.52	54.31	t
Belderrig, Ireland	UCD-C18	4150	60	-9.54	54.31	t
Belderrig, Ireland	UCD-C49	4580	60	-9.54	54.31	t
Belderrig, Ireland	UCD-C07	3330	50	-9.57	54.30	t
Belderrig, Ireland	UCD-C31	4510	50	-9.56	54.30	t

Location	Lab code	Date (uncalibrated yr BP)	±S.D.	Longitude	Latitude	Source
Belderrig, Ireland	UCD-C58	3960	60	-9.58	54.30	t
Belderrig, Ireland	UCD-C60	3930	50	-9.56	54.30	t
Belderrig, Ireland	UCD-C47	4210	60	-9.56	54.31	t
Annagh More, Ireland	UCD-C26	4350	60	-9.36	54.25	t
Annagh More, Ireland	UCD-C50	4440	60	-9.36	54.25	t
Annagh More, Ireland	UCD-C24	4440	60	-9.35	54.23	t
Annagh More, Ireland	UCD-C38	3820	60	-9.35	54.23	t
Erris Region, Ireland	UCD-C01	4240	60	-9.87	54.24	t
Erris Region, Ireland	UCD-C02	4340	60	-9.75	54.25	t
Erris Region, Ireland	UCD-C12	3950	60	-9.76	54.26	t
Erris Region, Ireland	UCD-C05	4250	60	-9.81	54.26	t
Erris Region, Ireland	UCD-C13	3990	60	-9.87	54.21	t
Erris Region, Ireland	UCD-C16	4490	60	-9.65	54.24	t
Erris Region, Ireland	UCD-C19	4530	60	-9.84	54.24	t
Erris Region, Ireland	UCD-C20	4230	60	-9.81	54.22	t
Erris Region, Ireland	UCD-C25	4460	60	-9.72	54.18	t
Erris Region, Ireland	UCD-C35	4440	50	-9.86	54.27	t
Erris Region, Ireland	UCD-C36	3090	50	-9.82	54.26	t
Erris Region, Ireland	UCD-C43	4080	60	-9.77	54.22	t
Erris Region, Ireland	UCD-C41	6720	90	-9.77	54.22	t
Erris Region, Ireland	UCD-C52	4070	60	-9.91	54.07	t
Erris Region, Ireland	UCD-C48	7530	100	-9.91	54.07	t
Over Wood Moss, England	Q-1404	7350	60	-1.84	53.45	u
Lady Clough Moor, England	Q-1350	4340	40	-1.84	53.43	u
Featherbed Moss, England	Q-1347	4320	40	-1.85	53.43	u
Laund Clough, England	Q1401	4250	40	-1.76	53.49	u
Tintwistle Knarr, England	Q-1405	4210	40	-1.95	53.49	u
Far Black Clough, England	Q-1406	3995	40	-1.82	53.49	u
Belderg Beg, England	?	4220	95	-9.57	54.30	t
Glenveagh, County Donegal, Ireland	?	3880	110	?	?	v
Glenveagh, County Donegal, Ireland	?	3850	100	?	?	v
Ladies View, Killarney, Ireland	?	1790	95	?	?	w
Ladies View, Killarney, Ireland	?	1810	95	?	?	w
Clonsast Bog, Ireland	?	1620	130	-7.22	53.22	x, y
Glashabaun, Ireland	?	3970	60	-6.99	53.31	z
Glashabaun, Ireland	?	3955	65	-6.99	53.31	z
Glashabaun, Ireland	?	3855	65	-6.99	53.31	z
Glashabaun, Ireland	?	3820	60	-6.99	53.31	z
Glashabaun, Ireland	?	3775	70	-6.99	53.31	z
Glashabaun, Ireland	?	3695	55	-6.99	53.31	z
Glashabaun, Ireland	?	3640	45	-6.99	53.31	z
Glashabaun, Ireland	?	3510	60	-6.99	53.31	z
Ballycon, Ireland	?	3730	65	-7.18	53.29	z
White Moss, England	SRR-3939	4510	40	-2.34	53.05	aa
White Moss, England	SRR-3940	4320	50	-2.34	53.05	aa
White Moss, England	SRR-3941	4160	40	-2.34	53.05	aa
White Moss, England	SRR-3943	4115	40	-2.34	53.05	aa
White Moss, England	SRR-3944	4090	50	-2.34	53.05	aa
White Moss, England	SRR-3942	4125	50	-2.34	53.05	aa
White Moss, England	SRR-3945	4015	45	-2.34	53.05	aa

Location	Lab code	Date (uncalibrated yr BP)	±S.D.	Longitude	Latitude	Source
White Moss, England	SRR-3946	4055	45	-2.34	53.05	aa
White Moss, England	SRR-3947	4645	35	-2.34	53.05	aa
White Moss, England	SRR-3948	4500	40	-2.34	53.05	aa
White Moss, England	SRR-4500	4505	40	-2.34	53.05	aa
White Moss, England	SRR-4501	4335	40	-2.34	53.05	aa
White Moss, England	SRR-6101	3905	45	-2.34	53.05	aa
White Moss, England	SRR-6102	3890	45	-2.34	53.05	aa
White Moss, England	SRR-6103	3535	45	-2.34	53.05	aa
White Moss, England	SRR-6104	3895	45	-2.34	53.05	aa
White Moss, England	SRR-6105	4210	45	-2.34	53.05	aa
White Moss, England	SRR-6106	4750	45	-2.34	53.05	aa
White Moss, England	SRR-6107	4305	45	-2.34	53.05	aa

7.2 Appendix II: Site diagrams and Wind/Palaeowind interpretation

Figure 94: Sample location map Borgie Forest

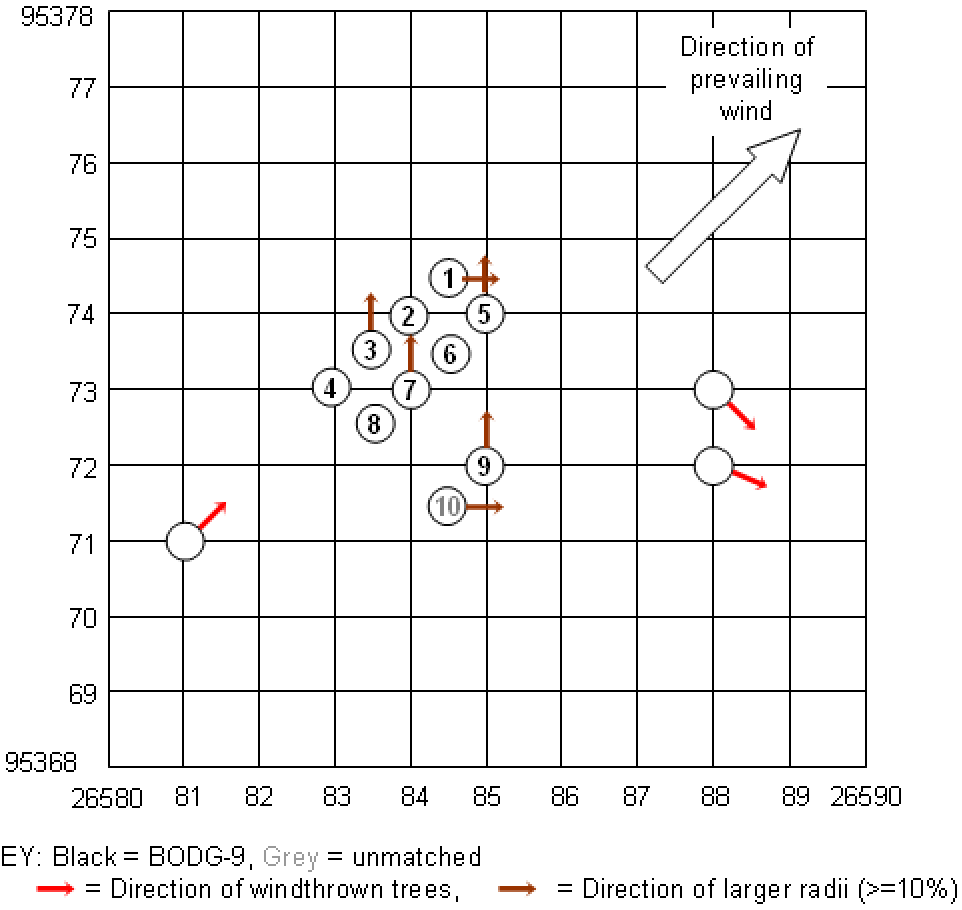


Figure 95: Sample location map of Eilean Sùbhainn site A

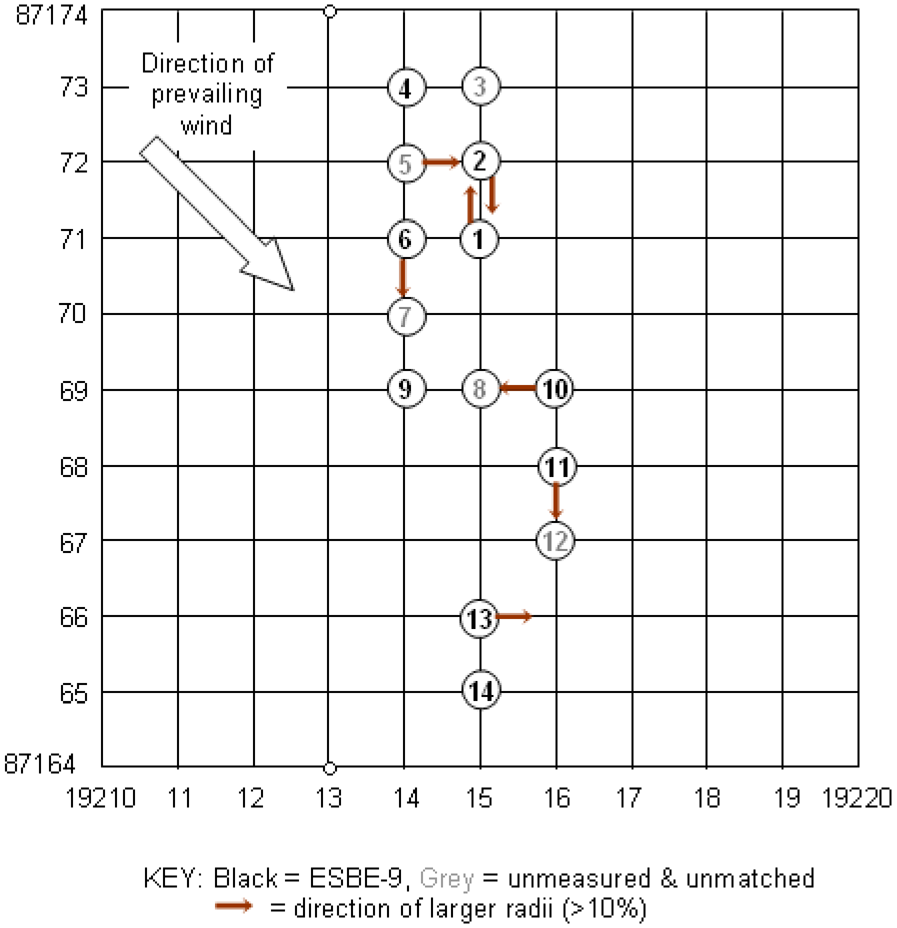


Figure 96: Sample location map of Eilean Sùbhainn site B

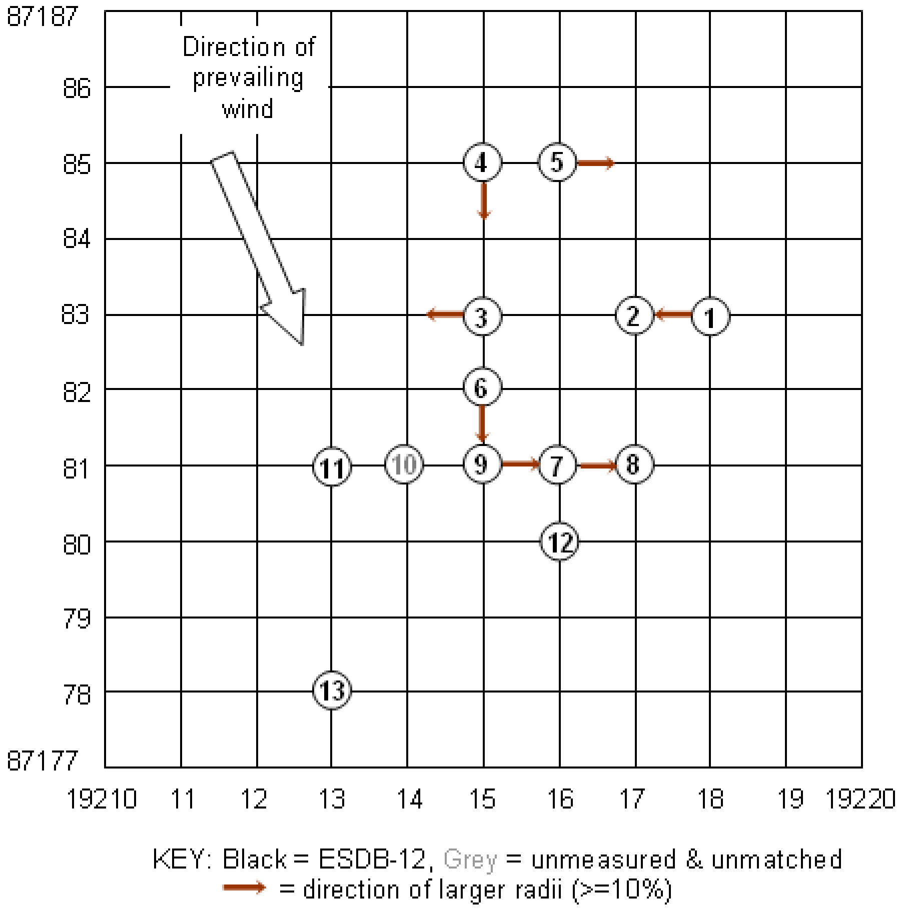
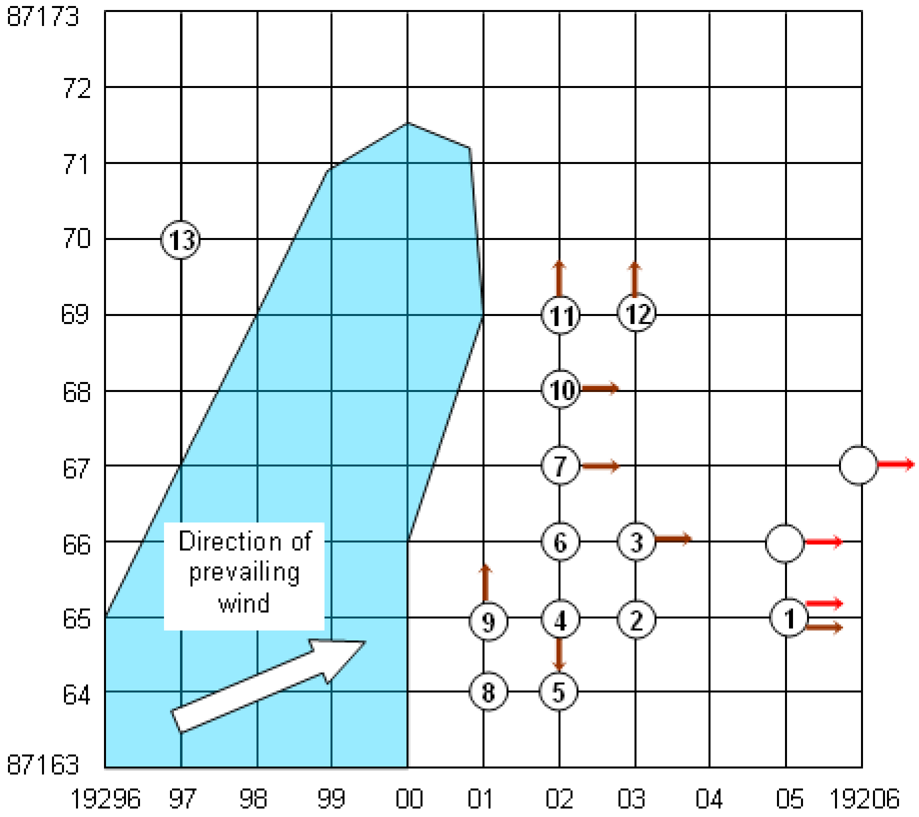
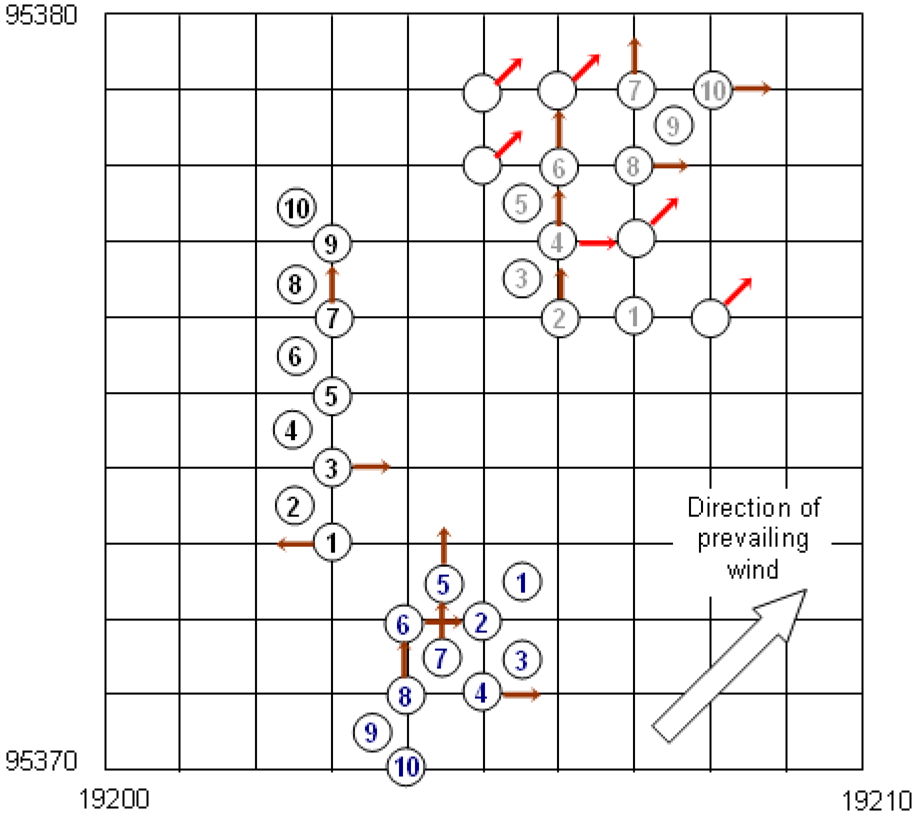


Figure 97: Sample location map of Eilean Sùbhainn site C



KEY: → = direction of larger radii (>=10%), → = direction of windthrown trees, blue = approximate position of loch edge.

Figure 98: Sample location map of Strathnaver Forest sites A, B and C



KEY: Blue = STIN, Grey = STPE, Black = STWB
→ = direction of wind thrown trees, → = direction of larger radii (>=10%)

Figure 99: Sample location diagram for Loch Assynt

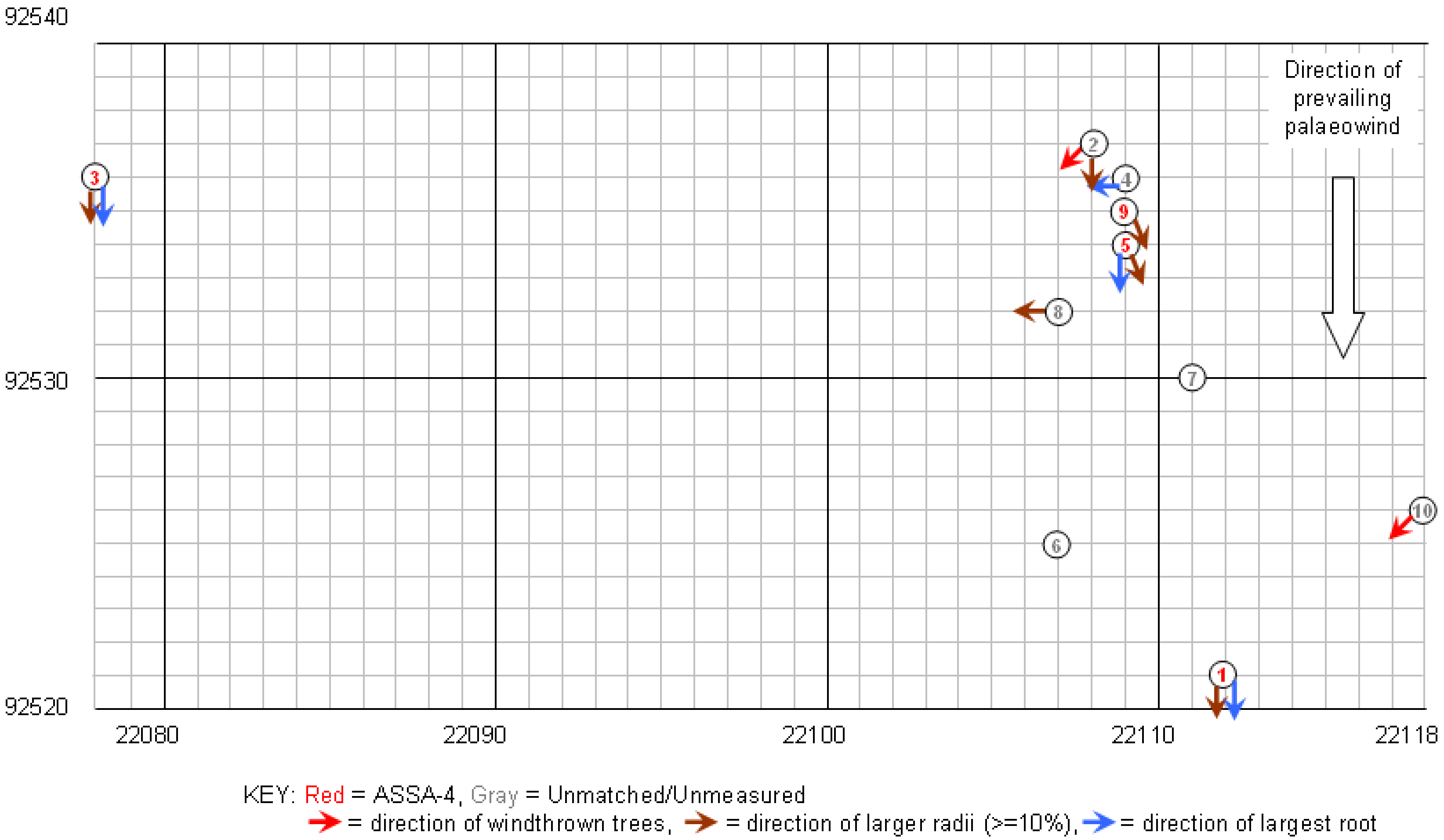
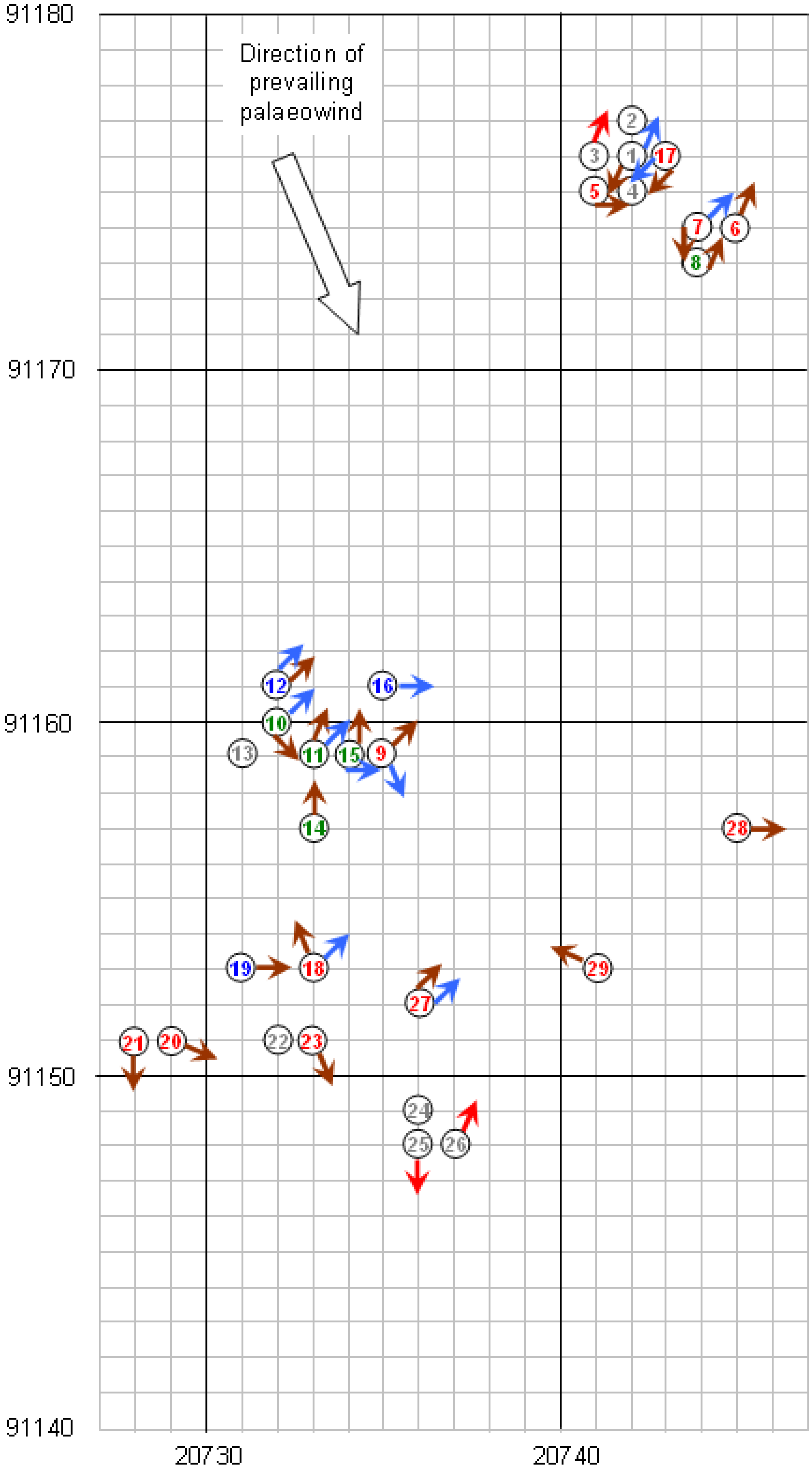


Figure 100: Sample location diagram of Druim Bad a'Ghall



KEY: Red = BADA-12, Green = BADA-B, Blue = BADA-C, Black = Unmatched,
Gray = Unmeasured
→ = direction of larger radii (>=10%), → = direction of largest root
→ = direction of windthrown trees

Figure 101: Sample location map of Polla on Loch Eriboll

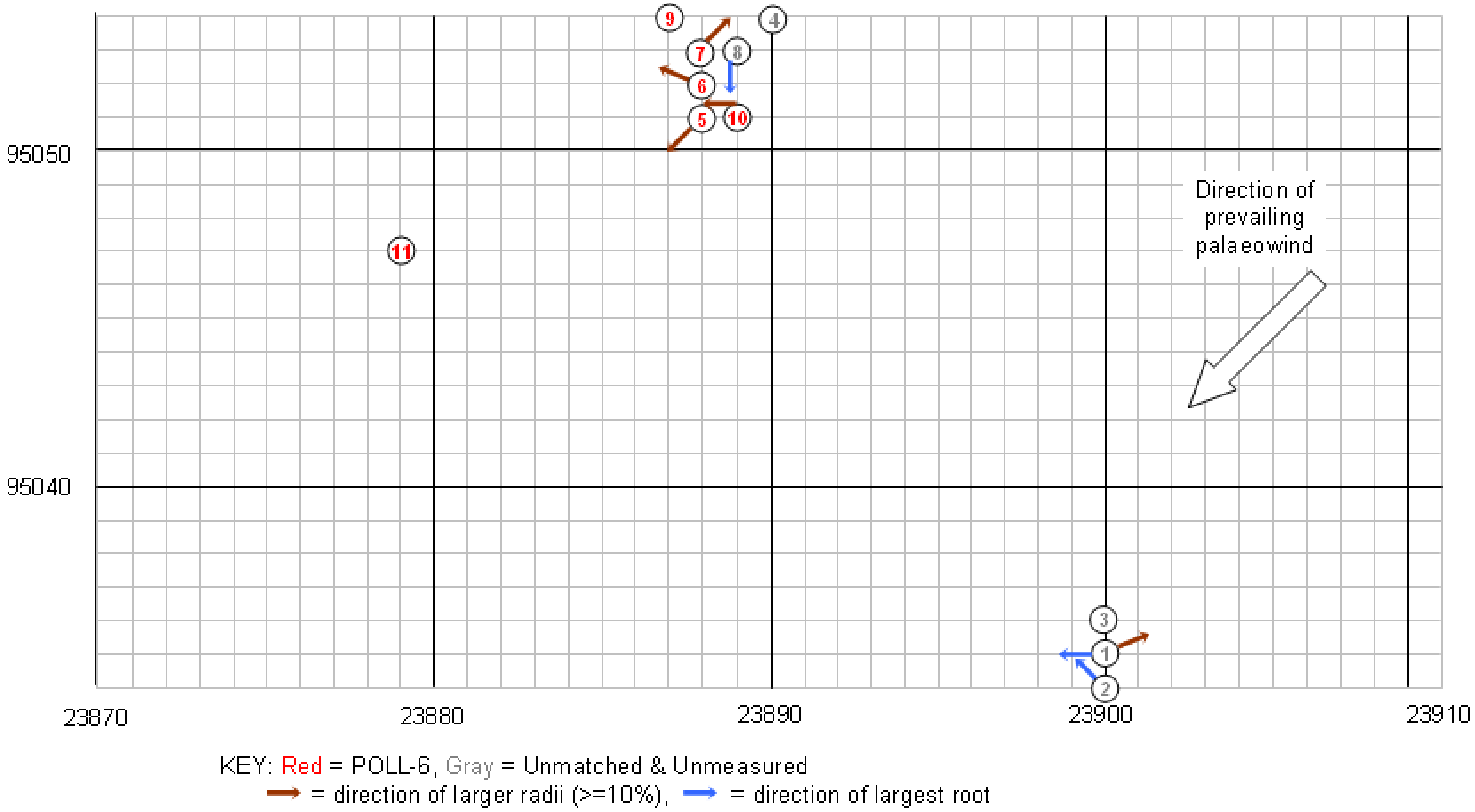


Figure 102: Sample location map of Loch an Ruathair

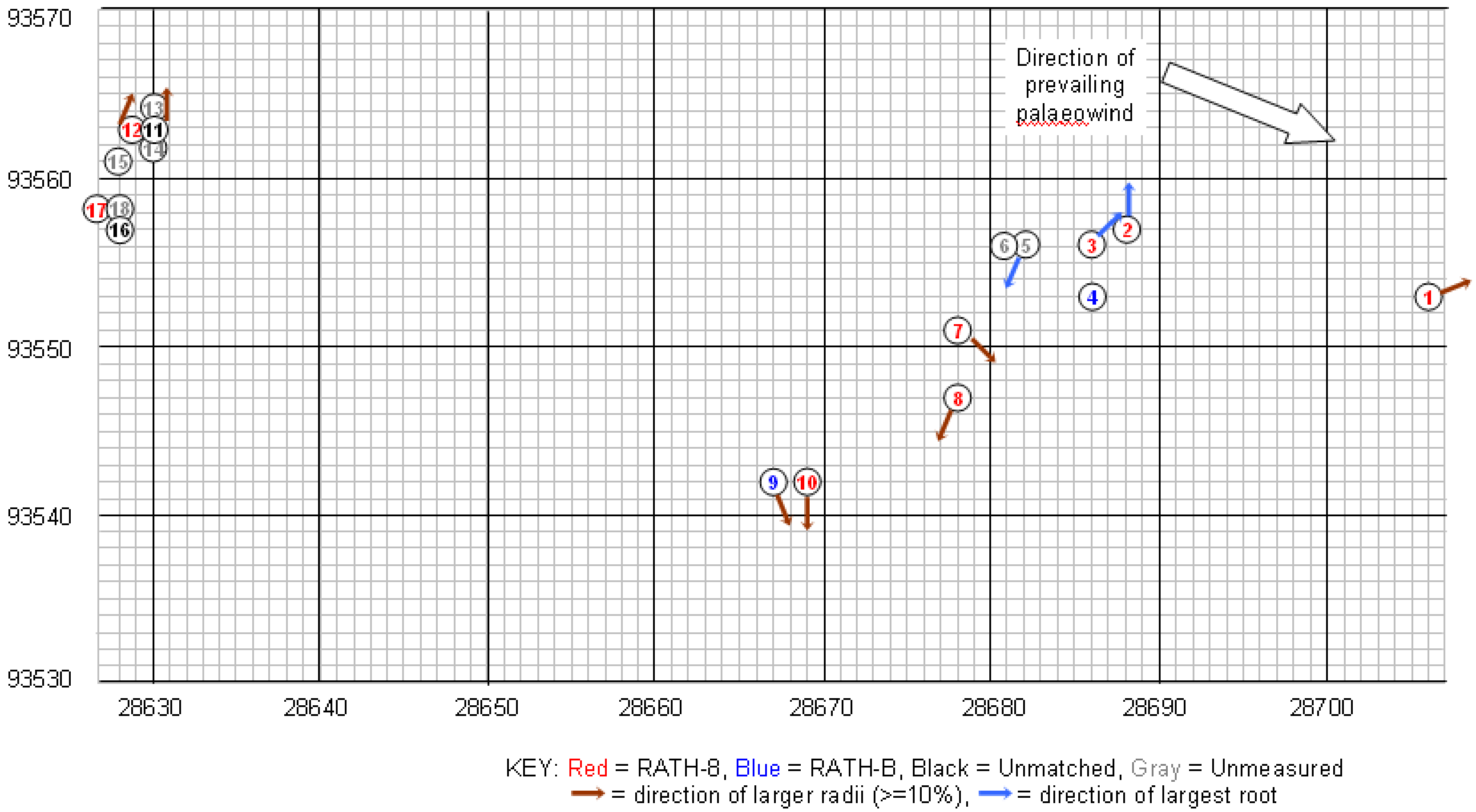


Figure 103: Sample location map of Skerricha

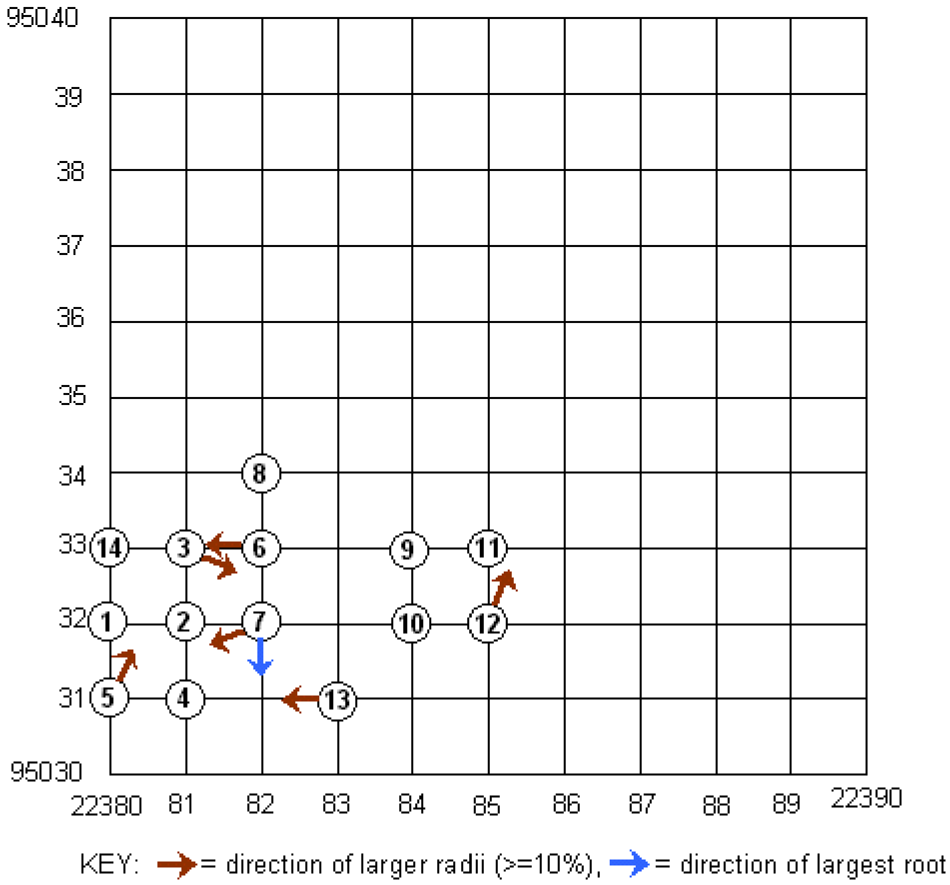
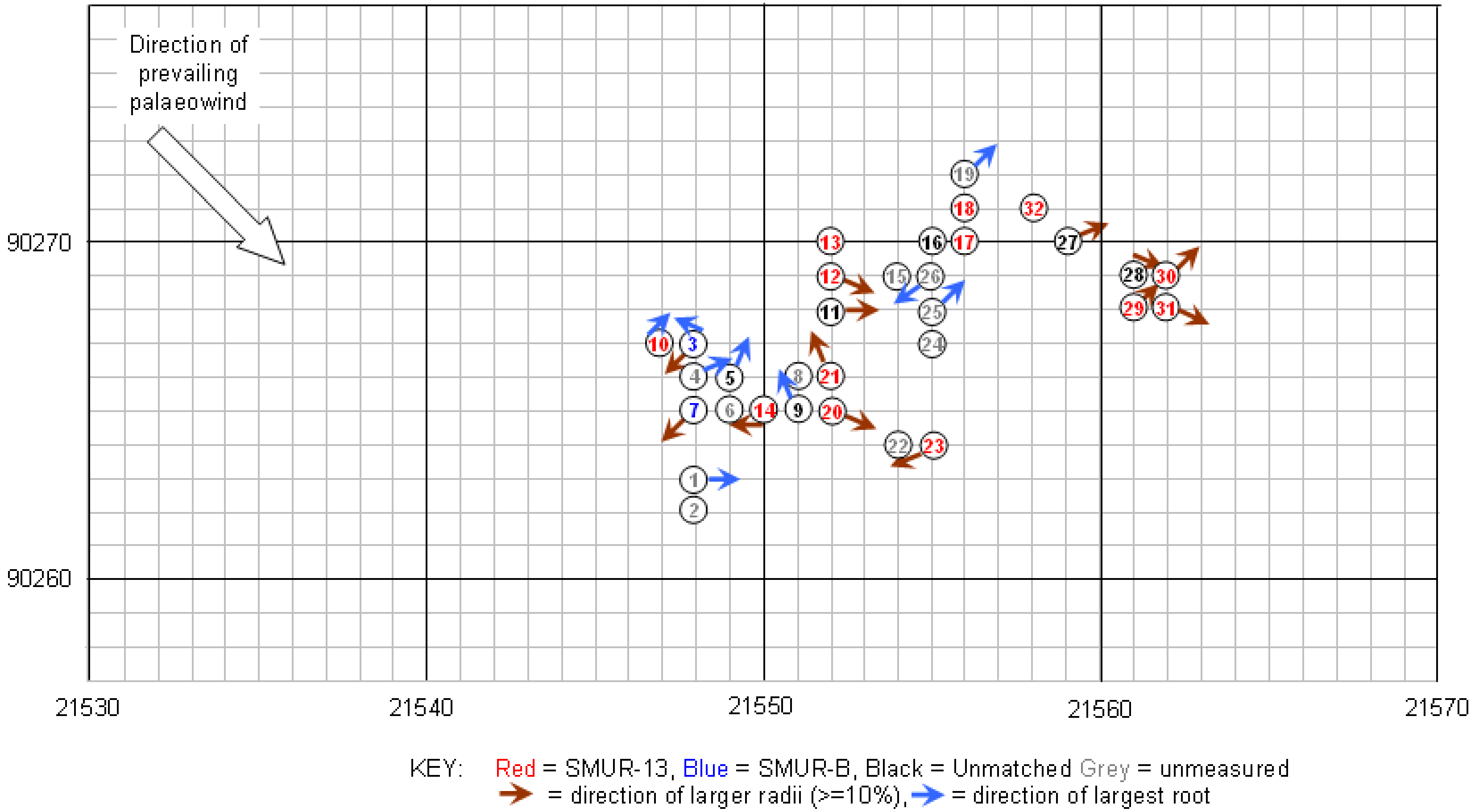


Figure 104: Sample location map of Strath Kanaird



7.3 Appendix III: Site Cross-matching

Table 23: Cross-matching between series from Abernethy

Filenames	Start date	End date	Chronology name	ABEA02	ABEA03	ABEA04	ABEA05	ABEA06	ABEA08	ABEA09	ABEA10	ABEA11	ABEA12	ABEA13	ABEA14	ABEA15	ABEA16	ABEA17	ABEB03	ABEB04	ABEB05	ABEB06	ABEB07	ABEB08	ABEC01	ABEC02	ABEC03	ABEC04	ABEC05	ABEC06A	ABEC06B	ABEC07	ABEC08A	ABEC08B	ABEC09A	ABEC09B	ABEC10	ABEC11	ABEC12	ABEC13	ABEC14	ABEC15	ABEC16	ABEC17A	ABEC17B	ABEC18A	ABEC18B	ABEC19	ABEC20	ABEC22	ABED01	ABED02	ABED04	ABED05	ABED06	ABED07	ABED08	ABED09	ABED10
ABEA01	AD1804	AD2000	ABEA-16	6.6	5.1	6.5	-	-	-	-	7.2	-	-	-	-	5.1	6.6	3.9	3.6	-	-	4.6	-	-	4.7	-	-	4.8	3.6	3.7	-	-	-	-	-	-	-	4.0	4.5	3.9	-	-	-	-	-	3.6	-	-	-	-	-	-	-	-	-	-	-	-	-
ABEA02	AD1809	AD1948	ABEA-16		4.9	6.1	-	3.7	-	-	3.8	-	3.5	-	-	3.8	9.3	3.5	-	5.3	-	-	3.9	4.6	-	-	-	4.2	5.1	-	-	-	-	\	-	-	-	3.9	6.6	4.7	-	-	-	-	-	-	\	-	-	4.2	\	\	\	-	\	\	\	\	\
ABEA03	AD1829	AD2000	ABEA-16			5.7	-	-	-	-	-	-	-	-	-	-	7.3	3.9	-	-	-	4.5	4.7	-	-	-	-	3.6	-	-	-	-	-	-	3.6	-	-	4.5	5.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.6	-	-	-	-	-
ABEA04	AD1810	AD2000	ABEA-16				-	5.2	-	-	7.5	-	-	4.6	3.8	5.2	8.2	5.2	-	4.5	-	-	5.6	4.4	5.0	3.8	-	5.2	5.2	-	-	-	4.1	-	-	-	4.0	-	6.5	4.6	-	-	3.8	-	-	6.0	-	-	4.7	-	-	-	-	-	-	-	-	-	-
ABEA05	AD1833	AD1913	ABEA-16					3.8	-	-	-	-	-	6.6	-	-	-	-	-	4.2	\	-	-	-	-	\	-	-	4.3	\	-	6.4	-	\	5.1	\	-	3.6	7.0	-	\	-	\	4.8	\	5.1	\	-	4.1	-	\	\	\	-	\	\	\	\	\
ABEA06	AD1869	AD2000	ABEA-16						-	4.1	5.0	5.1	5.1	4.7	3.7	5.7	5.5	6.3	4.6	5.6	-	4.6	4.0	6.0	3.7	-	4.7	4.7	5.4	-	-	4.8	5.7	-	-	4.1	-	6.5	7.8	8.2	-	3.8	3.6	-	-	4.9	-	4.1	5.1	3.9	-	-	-	-	-	-	-	-	-
ABEA08	AD1854	AD2000	ABEA-16							-	4.4	4.2	4.0	-	-	-	-	-	-	-	-	-	3.7	4.6	-	-	3.8	-	-	-	-	-	-	4.1	-	-	-	4.0	-	4.1	5.2	3.6	-	-	-	-	-	-	-	5.0	-	3.5	-	-	-	-	-	-	-
ABEA09	AD1871	AD2000	ABEA-16								-	-	4.0	-	-	-	-	-	-	-	-	4.9	4.5	-	-	-	-	-	4.3	4.2	-	-	-	-	-	-	-	-	4.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ABEA10	AD1798	AD2000	ABEA-16									-	-	4.5	-	4.9	4.4	4.7	3.8	3.9	-	-	5.8	-	5.1	-	-	4.3	3.7	4.5	3.9	-	-	-	-	-	4.5	5.0	4.1	-	-	4.1	3.9	-	-	4.5	-	-	-	-	3.6	-	-	-	-	-	-	-	-
ABEA11	AD1866	AD2000	ABEA-16										4.9	-	4.3	4.0	4.5	4.4	4.8	5.4	4.4	3.6	-	4.2	4.9	-	4.2	4.0	-	-	-	-	-	-	-	-	-	6.2	4.9	3.5	-	-	-	-	-	-	-	3.7	-	4.1	-	-	-	-	-	-	-	-	-
ABEA12	AD1866	AD2000	ABEA-16											-	4.5	-	5.6	-	4.4	5.8	5.3	4.3	4.1	5.1	-	-	4.1	4.2	5.8	-	-	-	-	-	-	-	-	4.9	5.4	6.7	5.1	5.9	6.7	-	-	-	-	-	-	5.1	-	-	-	4.5	-	-	-	-	-
ABEA13	AD1846	AD2000	ABEA-16												3.9	4.1	5.0	4.7	4.9	7.7	-	3.7	4.5	5.1	5.5	5.5	6.5	4.0	4.5	4.3	4.0	5.4	4.5	-	-	-	-	4.3	6.9	7.3	4.1	4.4	7.6	4.5	-	5.5	-	-	5.3	5.0	-	-	-	-	-	-	-	-	-
ABEA14	AD1816	AD2000	ABEA-16													-	-	3.9	5.7	5.7	-	-	-	3.9	4.6	3.8	4.3	5.2	3.8	-	-	-	5.0	-	-	-	-	-	4.0	3.9	-	4.3	-	-	-	-	-	4.0	-	3.8	-	-	-	-	-	-	-	-	-
ABEA15	AD1869	AD2000	ABEA-16														-	5.9	-	4.7	4.6	3.7	5.7	4.4	8.0	4.3	3.7	6.5	-	6.7	-	-	-	-	-	5.5	-	6.2	7.0	6.1	-	-	4.6	-	3.7	3.9	-	-	4.6	5.2	-	-	-	-	-	-	-	-	-
ABEA16	AD1817	AD2000	ABEA-16															4.6	3.8	4.6	3.8	-	4.4	4.6	-	-	-	5.3	5.4	-	-	4.2	-	-	-	-	-	5.2	6.9	3.6	-	4.6	-	3.8	-	-	-	-	3.5	3.9	-	-	-	3.9	-	-	-	-	-
ABEA17	AD1840	AD2000	ABEA-16																-	5.0	4.5	4.1	5.5	7.7	3.7	4.2	3.7	4.1	4.4	3.6	-	-	4.6	3.6	-	4.9	-	4.5	8.6	6.2	-	-	3.8	-	-	4.7	3.6	4.9	3.9	4.3	-	-	-	-	-	-	4.6	-	-
ABEB03	AD1866	AD2000	ABEB-06																	4.3	4.0	3.8	-	4.2	5.9	5.1	5.9	4.2	-	4.5	-	4.6	-	-	-	-	3.7	5.8	4.3	3.7	-	4.7	-	-	-	4.0	-	-	3.9	-	-	-	-	-	-	-	-	-	-
ABEB04	AD1855	AD2000	ABEB-06																		5.0	6.7	4.2	7.1	4.8	5.4	7.8	4.3	5.5	-	-	4.7	5.7	-	-	-	-	5.7	7.2	9.2	3.7	6.1	7.3	-	5.6	5.5	-	5.0	4.7	7.0	-	-	-	-	-	4.2	-	-	-
ABEB05	AD1905	AD2000	ABEB-06																			4.3	-	5.5	4.0	-	4.2	4.4	-	3.6	\	-	-	-	-	-	3.8	6.1	3.6	3.8	3.9	5.1	5.6	\	3.8	\	-	-	-	3.6	-	-	-	-	-	3.7	-	-	-
ABEB06	AD1873	AD2000	ABEB-06																				5.3	4.4	-	-	4.9	-	5.3	-	-	-	-	-	4.0	-	-	6.1	6.5	5.1	-	4.8	4.1	-	3.6	-	-	-	5.5	4.8	-	5.3	-	3.9	4.1	-	-	-	-
ABEB07	AD1694	AD2000	ABEB-06																					4.9	-	3.7	4.5	-	5.4	4.0	-	-	-	-	-	4.2	-	4.4	8.2	5.1	-	-	-	3.9	-	-	3.7	3.6	4.3	6.7	-	-	-	4.4	-	-	-	3.6	-
ABEB08	AD1880	AD2000	ABEB-06																						-	3.7	6.1	5.9	-	-	-	-	4.3	4.8	4.4	4.5	-	6.2	8.6	8.6	3.7	3.9	5.6	-	3.7	3.8	-	-	3.5	7.1	-	-	-	-	-	-	-	4.3	-
ABEC01	AD1861	AD2000	ABEC-21																							5.2	3.9	8.4	-	5.3	4.3	4.7	3.8	-	-	-	-	4.5	4.9	4.7	-	4.3	4.3	-	-	4.7	-	-	3.6	-	-	-	-	-	-	3.6	-	-	-
ABEC02	AD1934	AD2000	ABEC-21																								3.8	4.5	\	3.6	\	\	\	-	\	-	5.0	3.7	-	6.3	-	-	4.3	\	3.8	\	4.1	-	-	-	-	-	-	3.5	-	-	-	-	-
ABEC03	AD1869	AD1999	ABEC-21																									4.7	3.7	-	-	4.1	4.5	4.9	-	-	-	6.7	6.5	7.6	4.6	5.4	6.4	-	4.5	-	-	4.8	4.6	6.5	-	4.8	-	-	-	4.2	-	3.5	-
ABEC04	AD1856	AD2000	ABEC-21																										-	3.6	4.4	3.6	5.2	-	-	4.1	-	4.7	4.7	5.0	4.2	4.7	3.6	-	3.6	3.8	-	-	4.1	5.6	-	-	-	-	3.9	-	-	4.0	-
ABEC05	AD1856	AD1942	ABEC-21																											-	5.3	3.6	5.0	\	3.8	-	-	4.4	6.8	4.3	-	3.8	-	3.6	-	5.3	\	-	4.6	4.2	\	\	\	-	\	\	\	\	\
ABEC06A	AD1922	AD2000	ABEC-21																												\	\	\	-	\	4.3	3.7	5.0	4.8	3.8	-	3.7	4.0	\	-	\	-	-	4.4	3.7	-	6.0	-	-	-	3.6	-	-	-
ABEC06B	AD1856	AD1918	ABEC-21																													-	4.2	\	-	\	-	3.6	-	-	\	-	\	-	\	4.0	\	-	-	-	\	\	\	-	\	\	\	\	\
ABEC07	AD1850	AD1929	ABEC-21																														4.1	\	5.0	\	-	3.6	5.4	-	\	3.5	4.0	4.6	\	6.1	\	-	6.1	3.6	\	\	\	-	\	\	\	\	\
ABEC08A	AD1854	AD1919	ABEC-21																															\	-	\	-	-	5.3	7.8	\	-	\	-	\	6.5	\	5.6	3.7	4.2	\	\	\	-	\	\	\	\	\
ABEC08B	AD1937	AD2000	ABEC-21																																\	-	-	-	-	-	-	-	-	\	-	\	-	5.6	-	-	3.7	-	-	-	-	-	-	4.0	-
ABEC09A	AD1845	AD1919	ABEC-21																																	\	-	4.9	6.6	5.6	\	-	\	4.2	\	3.9	\	-	4.9	-	\	\	\	-	\	\	\	\	\
ABEC09B	AD1925	AD2000	ABEC-21																																		-	-	5.5	3.6	-	-	-	\	3.8	\	-	-	-	3.6	-	3.8	-	-	-	-	-	-	-
ABEC10	AD1855	AD2000	ABEC-21																																			5.0	3.7	-	5.1	-	-	-	-	-	-	-	-	-	-	3.7	-	-	3.6	-	-	-	-
ABEC11	AD1838	AD2000	ABEC-21																																				8.0	5.4	4.9	5.7	6.7	4.2	3.6	4.0	-	3.8	6.7	5.7	-	4.8	-	-	-	-	-	-	-
ABEC12	AD1855	AD2000	ABEC-21																																					9.5	-	-	5.4	6.1	-	7.0	4.0	3.9	6.3	6.0	-	-	-	-	-	-	-	-	-
ABEC13	AD1890	AD2000	ABEC-21																																						3.9	5.0	6.6	\	4.1	5.5	-	3.5	3.6	6.3	-	-	-	3.6	-	-	-	-	-
ABEC14	AD1920	AD2000	ABEC-21																																							5.3	6.0	\	-	\	-	-	-	5.5	-	-	-	3.9	-	-	-	-	-
ABEC15	AD1896	AD2000	ABEC-21																																								5.6	\	4.3	-	-	-	4.5	5.1	-	-	-	3.9	-	-	-	-	-
ABEC16	AD1908	AD2000	ABEC-21																																									\	-	\	-	-	5.0	5.5	-	-	-	-	-	-	-	-	-
ABEC17A	AD1851	AD1899	ABEC-21																																										\	-	\	-	4.1	-	\	\	\	-	\	\	\	\	\
ABEC17B	AD1926	AD2000	ABEC-21																																											\	-	-	-	-	-	4.6	-	-	-	3.6	-	4.6	-
ABEC18A	AD1856	AD1915	ABEC-21																																												\	-	5.4	-	\	\	\	-	\	\	\	\	\
ABEC18B	AD1942	AD2000	ABEC-21																																													4.4	-	-	-	-	-	-	-	-	-	-	-
ABEC19	AD1871	AD2000	ABEC-21																																														-	5.4	4.6	-	-	-	-	-	-	5.0	-
ABEC20	AD1844	AD2000	ABEC-21																																															4.7	-	-	-	-	-	-	-	4.5	-
ABEC22	AD1863	AD2000	ABEC-21																																																-	-	-	3.7	4.6	-	-	5.1	-
ABED01	AD1938	AD2000	ABED-09																																																	-	4.9	-	4.2	-	-	6.6	5.1
ABED02	AD1950	AD2000	ABED-09																																																		-	3.6	3.5	-	-	5.0	-
ABED04	AD1952	AD2000	ABED-09																																																			-	-	4.3	-	3.5	-
ABED05	AD1882	AD2000	ABED-09																																																				-	-	-	-	-
ABED06	AD1940	AD2000	ABED-09																																																					-	-	5.6	3.6
ABED07	AD1955	AD2000	ABED-09																																																						-	-	-
ABED08	AD1946	AD2000	ABED-09																																																							5.3	-
ABED09	AD1936	AD2000	ABED-09																																																								5.4
ABED10	AD1937	AD2000	ABED-09																																																								

KEY: \ = overlap < 15 years, - = t-values less than 3.50.

Statistics: ALL n = 1458 min t = -2.55 max t = 9.53 mean t = 3.10 SD = 1.75
ABEC n = 273 min t = -0.35 max t = 9.53 mean t = 3.61 SD = 1.67
ABEA n = 120 min t = 0.12 max t = 9.34 mean t = 3.70 SD = 1.64
ABED n = 36 min t = 0.54 max t = 6.64 mean t = 3.18 SD = 1.38
ABEB n = 15 min t = 1.78 max t = 7.10 mean t = 4.57 SD = 1.25

Table 24: Cross-matching between series from Achanalt

Filenames	Start Date	End Date	Chronology name	02	03	04	05	06	08
ACHA01	AD1894	AD2004	ACHA-07	-	-	-	-	4.8	-
ACHA02	AD1893	AD2004	ACHA-07		5.1	3.8	6.5	5.7	5.8
ACHA03	AD1895	AD2004	ACHA-07			4.0	5.4	4.6	6.0
ACHA04	AD1894	AD2004	ACHA-07				4.3	-	-
ACHA05	AD1895	AD2004	ACHA-07					6.7	9.5
ACHA06	AD1894	AD2004	ACHA-07						4.3
ACHA08	AD1896	AD2004	ACHA-07						

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: ACHA-07, n = 21, min t = 1.62, max t = 9.53, mean t = 4.51, SD = 1.81

Table 25: Cross-matching between series from Ballochbuie

Filenames	Start date	End date	Chronology name	56802	56803	56804	56805	56806	56807	56808	56809	56810	56811
56801	AD1747	AD1862	BALLOCHB	3.8	4.5	-	3.7	5.2	-	4.6	3.9	-	3.6
56802	AD1712	AD1978	BALLOCHB		5.7	8.3	8.0	7.5	9.5	5.0	5.4	5.8	4.6
56803	AD1740	AD1978	BALLOCHB			5.3	8.4	7.3	5.8	5.5	5.9	6.1	4.6
56804	AD1728	AD1978	BALLOCHB				6.8	6.7	8.6	6.1	4.9	4.3	-
56805	AD1770	AD1978	BALLOCHB					7.1	8.8	8.0	5.7	5.0	5.0
56806	AD1724	AD1978	BALLOCHB						7.9	7.5	6.0	5.2	5.8
56807	AD1729	AD1978	BALLOCHB							8.5	6.1	4.6	3.8
56808	AD1720	AD1978	BALLOCHB								7.1	4.1	6.1
56809	AD1761	AD1978	BALLOCHB									4.3	8.0
56810	AD1732	AD1978	BALLOCHB										8.9
56811	AD1762	AD1978	BALLOCHB										

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: BALLOCHB, n = 55, min t = 2.78, max t = 9.54, mean t = 5.84, SD = 1.73

Table 26: Cross-matching between series from Beinn Eighe

Filenames	Start date	End date	Chronology name	B2	B26	B27	B28	C6	D10	D3	D6	D9
B1	AD1828	AD1979	BNAA-10	5.2	5.0	-	5.5	-	-	-	3.8	5.8
B2	AD1809	AD1989	BNAA-10		5.9	-	3.7	-	-	-	-	-
B26	AD1833	AD1980	BNAA-10			4.9	3.6	-	-	-	4.1	3.5
B27	AD1832	AD1920	BNAA-10				3.8	-	-	-	-	-
B28	AD1826	AD1989	BNAA-10					-	-	3.7	-	4.6
C6	AD1833	AD1989	BNAA-10						4.0	5.4	4.4	3.6
D10	AD1887	AD1989	BNAA-10							4.7	4.0	6.2
D3	AD1863	AD1980	BNAA-10								4.9	5.7
D6	AD1869	AD1989	BNAA-10									5.3
D9	AD1825	AD1989	BNAA-10									

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: BNAA-10, n = 45, min t = 0.51, max t = 6.15, mean t = 3.60, SD = 1.57

Table 27: Cross-matching between series from Borgie Forest

Filenames	Start date	End date	Chronology name	02	03	04	05B	06	07A	08B	09
BODG01	AD1967	AD2005	BODG-09	-	4.1	5.3	-	3.8	-	-	5.1
BODG02	AD1967	AD2003	BODG-09		6.2	-	-	-	-	-	-
BODG03	AD1966	AD2005	BODG-09			3.9	-	-	-	-	-
BODG04	AD1969	AD2005	BODG-09				4.3	5.8	-	5.8	8.4
BODG05B	AD1966	AD2003	BODG-09					-	4.3	4.1	-
BODG06	AD1965	AD2002	BODG-09						4.0	-	4.6
BODG07A	AD1964	AD2002	BODG-09							-	-
BODG08B	AD1967	AD2005	BODG-09								4.4
BODG09	AD1964	AD2005	BODG-09								

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: BODG-09, n = 36, min t = 1.69, max t = 8.43, mean t = 3.58, SD = 1.45

Table 28: Cross-matching between series from Carrbridge

Filenames	Start date	End date	Chronology name	CFG02	CFG03	CFG04	CFG05	CFG06	CFG07	CFG08	CFG09	CFG10	CFG11	CFG12	CFG13
CFG01	AD1889	AD1979	CFG-13	4.1	4.9	4.0	4.1	4.3	3.6	4.2	-	3.6	-	-	-
CFG02	AD1882	AD1979	CFG-13		5.2	-	5.0	4.3	-	4.9	4.5	-	-	3.8	5.4
CFG03	AD1890	AD1979	CFG-13			6.1	-	-	5.6	4.2	4.2	4.0	4.4	5.1	4.9
CFG04	AD1881	AD1976	CFG-13				-	-	4.6	3.7	-	3.5	-	4.9	6.1
CFG05	AD1896	AD1979	CFG-13					5.4	4.0	4.3	4.6	4.3	3.5	-	8.2
CFG06	AD1887	AD1979	CFG-13						3.8	3.8	5.3	-	3.8	-	4.7
CFG07	AD1887	AD1979	CFG-13							4.2	4.6	4.9	5.3	4.8	5.0
CFG08	AD1884	AD1979	CFG-13								-	4.6	4.1	3.8	6.8
CFG09	AD1888	AD1979	CFG-13									-	3.9	-	4.2
CFG10	AD1882	AD1979	CFG-13										-	5.8	6.0
CFG11	AD1890	AD1979	CFG-13											-	5.0
CFG12	AD1880	AD1979	CFG-13												3.8
CFG13	AD1885	AD1979	CFG-13												

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: CFG-13, n = 78 min t = 1.52 max t = 8.20 mean t = 4.07 SD = 1.20

Table 29: Cross-matching between series from Coulin

Filenames	Start date	End date	Chronology name	57002	57003	57004	57005	57006	57007	57008	57009	57010	57011	57209
57001	AD1825	AD1978	COULIN	6.3	5.8	5.7	6.2	-	-	-	4.9	-	3.7	6.0
57002	AD1687	AD1978	COULIN		4.1	6.7	6.1	-	-	4.1	8.5	4.9	-	-
57003	AD1702	AD1978	COULIN			7.7	5.8	-	3.8	4.9	8.4	5.9	4.3	4.7
57004	AD1807	AD1978	COULIN				7.1	-	3.6	5.9	6.8	3.9	6.9	
57005	AD1793	AD1978	COULIN					-	-	-	6.7	-	5.6	
57006	AD1722	AD1978	COULIN						4.9	3.5	4.2	4.3	-	
57007	AD1690	AD1960	COULIN							6.1	-	7.0	-	
57008	AD1705	AD1978	COULIN								4.9	6.1	-	5.7
57009	AD1809	AD1978	COULIN									4.0	5.8	-
57010	AD1671	AD1978	COULIN										3.7	5.4
57011	AD1833	AD1978	COULIN											5.8

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: COULIN, n = 55 min t = 0.65 max t = 8.45 mean t = 4.56 SD. = 1.82

Table 30: Cross-matching between series from Creag Fhiaclach – A

Filenames	Start date	End date	Chronology name	CFA02	CFA03	CFA04	CFA05	CFA06	CFA07	CFA08	CFA09	CFA10	CFA11	CFA12	CFA13	CFA14	CFA15
CFA01	AD1880	AD1979	CFA-15	4.8	6.9	5.3	7.0	5.9	-	6.1	3.5	5.7	4.6	3.8	4.1	5.5	6.1
CFA02	AD1880	AD1979	CFA-15		7.0	5.7	6.8	8.2	4.6	6.1	4.5	6.7	6.0	7.3	4.8	7.2	6.1
CFA03	AD1880	AD1979	CFA-15			7.2	8.4	7.2	5.0	9.3	4.5	7.9	6.5	5.8	6.8	7.8	5.2
CFA04	AD1880	AD1979	CFA-15				6.2	4.9	6.2	5.8	5.6	6.2	3.8	6.8	5.8	7.5	5.3
CFA05	AD1880	AD1979	CFA-15					6.8	7.1	8.1	4.6	10.1	5.6	7.4	7.0	9.0	6.8
CFA06	AD1880	AD1979	CFA-15						5.4	7.0	5.8	6.4	5.2	5.6	5.6	6.1	6.8
CFA07	AD1880	AD1979	CFA-15							4.9	4.5	8.1	3.6	5.3	6.0	6.1	5.4
CFA08	AD1880	AD1979	CFA-15								3.7	6.7	6.0	4.8	6.1	6.7	6.4
CFA09	AD1880	AD1979	CFA-15									5.0	-	4.3	5.6	5.0	5.4
CFA10	AD1880	AD1979	CFA-15										6.0	7.8	11.1	9.6	8.6
CFA11	AD1880	AD1979	CFA-15											4.8	4.8	7.2	4.4
CFA12	AD1880	AD1979	CFA-15												8.8	9.4	5.8
CFA13	AD1880	AD1979	CFA-15													9.9	7.1
CFA14	AD1880	AD1979	CFA-15														7.4
CFA15	AD1880	AD1979	CFA-15														

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: CFA-15, n = 105 min t = 1.66 max t = 11.06 mean t = 6.17 SD = 1.59

Table 31: Cross-matching between series from Creag Fhiaclach – B

Filenames	Start date	End date	Chronology name	CFB02	CFB03	CFB05	CFB07	CFB08	CFB09	CFB10	CFB11	CFB12
CFB01	AD1880	AD1979	CFB-10	7.1	4.5	5.5	7.5	-	5.8	-	-	5.1
CFB02	AD1880	AD1979	CFB-10		4.2	8.0	7.8	5.3	5.6	-	5.8	5.4
CFB03	AD1885	AD1979	CFB-10			-	6.0	5.0	-	5.2	-	3.8
CFB05	AD1880	AD1979	CFB-10				4.0	5.4	-	-	4.6	5.0
CFB07	AD1880	AD1979	CFB-10					4.9	6.9	5.4	5.1	4.3
CFB08	AD1880	AD1979	CFB-10						5.1	6.3	13.3	6.8
CFB09	AD1880	AD1979	CFB-10							4.8	5.5	5.8
CFB10	AD1880	AD1979	CFB-10								5.2	7.3
CFB11	AD1880	AD1979	CFB-10									6.1
CFB12	AD1880	AD1979	CFB-10									

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: CFB-10, n = 45 min t = 2.34 max t = 13.29 mean t = 5.24 SD = 1.87

Table 32: Cross-matching between series from Creag Fhiaclach – C

Filenames	Start date	End date	Chronology name	CFC06	CFC09
CFC01	AD1915	AD1979	CFC-03	5.9	3.7
CFC06	AD1880	AD1979	CFC-03		4.6
CFC09	AD1885	AD1979	CFC-03		

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: CFC-03, n = 3 min t = 3.74 max t = 5.89 mean t = 4.74 SD = 0.89

Table 33: Cross-matching between series from Creag Fhiaclach – D

Filenames	Start date	End date	Chronology name	CFD02	CFD03	CFD04	CFD05	CFD06	CFD07	CFD09	CFD11	CFD12	CFD16
CFD01	AD1880	AD1979	CFD-11	5.7	4.9	4.5	7.2	7.9	5.9	5.0	-	4.9	6.0
CFD02	AD1880	AD1979	CFD-11		5.4	8.1	7.3	8.3	5.2	4.1	-	4.9	7.2
CFD03	AD1880	AD1979	CFD-11			-	4.4	6.7	3.7	5.7	6.2	4.3	4.3
CFD04	AD1880	AD1979	CFD-11				7.3	5.8	5.1	3.8	-	4.1	5.6
CFD05	AD1880	AD1979	CFD-11					6.8	8.4	5.0	4.2	6.1	7.2
CFD06	AD1880	AD1979	CFD-11						7.7	5.0	5.0	4.3	7.0
CFD07	AD1880	AD1979	CFD-11							4.8	-	4.6	6.2
CFD09	AD1880	AD1979	CFD-11								4.8	6.8	4.0
CFD11	AD1880	AD1979	CFD-11									-	-
CFD12	AD1880	AD1979	CFD-11										3.8
CFD16	AD1880	AD1979	CFD-11										

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: CFD-11, n = 55 min t = 2.59 max t = 8.38 mean t = 5.32 SD = 1.51

Table 34: Cross-matching between series from Creag Fhiaclach – E

Filenames	Start date	End date	Chronology name	CFE02	CFE03	CFE04	CFE06	CFE07	CFE08	CFE10	CFE13
CFE01	AD1880	AD1979	CFE-09	-	-	-	-	3.7	-	-	-
CFE02	AD1880	AD1979	CFE-09		-	5.0	4.2	4.6	4.8	-	-
CFE03	AD1880	AD1979	CFE-09			-	-	3.7	3.9	4.9	-
CFE04	AD1880	AD1979	CFE-09				4.7	3.8	4.0	4.1	4.1
CFE06	AD1880	AD1979	CFE-09					3.6	4.6	3.8	-
CFE07	AD1880	AD1979	CFE-09						5.1	5.3	-
CFE08	AD1880	AD1979	CFE-09							3.7	4.4
CFE10	AD1880	AD1979	CFE-09								3.9
CFE13	AD1880	AD1979	CFE-09								

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: CFE-09, n = 36 min t = 0.63 max t = 5.34 mean t = 3.50 SD = 1.09

Table 35: Cross-matching between series from Creag Fhiaclach – F

Filenames	Start date	End date	Chronology name	CFF02	CFF03	CFF04	CFF05	CFF06	CFF07	CFF10	CFF11	CFF12	CFF14
CFF01	AD1880	AD1979	CFF-11	6.8	-	4.5	5.9	-	-	-	5.5	4.0	-
CFF02	AD1896	AD1979	CFF-11		-	-	6.1	-	-	-	4.7	4.8	-
CFF03	AD1880	AD1979	CFF-11			-	4.3	6.9	5.4	3.8	-	5.8	3.8
CFF04	AD1885	AD1979	CFF-11				5.5	-	4.8	-	-	-	-
CFF05	AD1889	AD1979	CFF-11					-	4.7	-	4.8	4.4	3.5
CFF06	AD1880	AD1979	CFF-11						5.0	7.9	-	-	-
CFF07	AD1880	AD1979	CFF-11							6.4	4.5	5.1	-
CFF10	AD1880	AD1979	CFF-11								-	-	-
CFF11	AD1880	AD1979	CFF-11									5.1	-
CFF12	AD1880	AD1978	CFF-11										-
CFF14	AD1890	AD1979	CFF-11										

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: CFF-11, n = 55, min t = -0.21, max t = 7.87, mean t = 3.68, SD = 1.69

Table 36: Cross-matching between series from Dimmie

Filenames	Start date	End date	Chronology name	37702	37703	37705	37806	37807	37808	37809	37810	37911	37912	37913
37701	AD1845	AD1976	DIMMIE	5.7	5.1	4.2	-	5.5	5.0	4.1	-	4.5	5.9	6.0
37702	AD1837	AD1974	DIMMIE		6.7	5.6	-	8.3	4.0	4.9	5.1	6.1	10.4	9.5
37703	AD1828	AD1976	DIMMIE			11.4	5.1	4.9	5.3	-	4.8	7.0	6.7	6.9
37705	AD1837	AD1976	DIMMIE				3.6	6.2	-	3.9	5.6	7.1	6.5	5.1
37806	AD1900	AD1976	DIMMIE					3.8	-	5.3	5.9	5.5	3.9	3.7
37807	AD1831	AD1976	DIMMIE						3.9	4.3	7.0	4.9	8.8	8.8
37808	AD1838	AD1976	DIMMIE							-	4.0	5.0	5.8	4.4
37809	AD1832	AD1976	DIMMIE								7.3	6.8	6.8	6.0
37810	AD1853	AD1976	DIMMIE									7.9	7.5	6.8
37911	AD1854	AD1976	DIMMIE										7.3	7.0
37912	AD1843	AD1976	DIMMIE											11.7
37913	AD1843	AD1976	DIMMIE											

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: DIMMIE, n = 66 min t = 2.46 max t = 11.65 mean t = 5.71 SD = 1.96

Table 37: Cross-matching between series from Eilann Sùbhainn

Filenames	Start date	End date	Chronology name	02	04-1	06	09B	10	11	13	14A	01	02	03	04	05	06	07	08A	09	11	12A	13	01	02	03	04	05	06	07	08	09	10	11	12	13A
ESBE01	AD1869	AD1968	ESBE-09	\	6.0	4.0	7.3	-	-	6.9	-	3.8	5.4	4.0	-	-	4.1	-	-	-	5.4	-	-	\	-	-	-	6.5	-	8.1	-	4.9	3.6	-	4.2	-
ESBE02	AD1957	AD2001	ESBE-09		\	3.6	\	-	4.1	-	3.8	-	-	-	-	-	-	-	-	-	-	-	-	-	\	-	\	-	\	-	\	\	-	-	-	-
ESBE04-1	AD1882	AD1941	ESBE-09			-	3.8	\	4.1	8.2	\	-	-	-	-	-	-	-	-	-	4.8	-	\	\	-	-	-	4.0	-	-	3.9	-	-	-	4.0	-
ESBE06	AD1891	AD2005	ESBE-09				-	3.6	3.7	6.9	4.5	4.3	5.1	5.2	6.1	3.8	-	4.6	-	3.6	3.7	-	5.4	4.7	-	-	-	-	-	4.5	-	-	-	-	-	4.3
ESBE09B	AD1874	AD1970	ESBE-09					-	-	8.1	-	3.6	6.1	-	-	-	4.5	-	-	-	-	-	-	\	3.6	-	-	4.2	-	5.4	-	4.7	-	-	-	-
ESBE10	AD1928	AD1979	ESBE-09						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.1	-	-	\	-	-	-	\	-	-	-	-	-
ESBE11	AD1901	AD2005	ESBE-09							3.7	5.2	-	-	-	-	-	-	-	-	-	-	-	-	4.2	-	-	-	-	-	-	-	-	-	-	-	-
ESBE13	AD1884	AD1999	ESBE-09								5.6	5.4	7.0	5.7	4.5	3.5	5.1	5.0	-	3.5	6.4	-	4.5	6.2	-	-	-	3.7	-	7.4	-	3.6	4.1	-	4.3	6.0
ESBE14A	AD1943	AD2000	ESBE-09									-	-	3.7	-	-	-	-	-	-	-	-	5.1	5.2	\	-	\	-	\	4.5	\	-	-	-	-	-
ESDB01	AD1917	AD2000	ESDB-12										7.8	5.8	3.5	3.8	-	4.6	-	-	5.1	-	-	-	-	4.6	-	-	-	6.3	-	-	5.2	-	3.9	3.6
ESDB02	AD1873	AD1979	ESDB-12											6.9	3.6	7.9	5.0	7.0	4.5	-	5.2	-	4.7	-	-	-	-	4.2	-	6.8	-	5.6	4.9	4.1	4.4	3.8
ESDB03	AD1790	AD1995	ESDB-12												5.1	4.3	3.9	4.4	-	5.4	7.0	4.5	4.1	3.7	-	-	-	-	-	4.5	-	-	-	-	3.5	-
ESDB04	AD1815	AD2005	ESDB-12													4.2	4.0	5.2	-	4.7	7.2	5.7	-	-	-	-	-	-	-	3.9	-	-	4.4	-	-	-
ESDB05	AD1882	AD2001	ESDB-12														4.9	6.7	4.7	4.2	4.6	-	4.0	-	-	-	-	-	-	5.0	-	-	-	-	-	-
ESDB06	AD1832	AD1974	ESDB-12															4.9	4.2	5.6	8.7	6.4	-	\	-	-	-	-	-	-	-	-	3.7	4.0	4.1	-
ESDB07	AD1844	AD2005	ESDB-12																4.9	4.6	7.5	3.6	3.7	4.0	-	3.5	-	-	-	6.0	-	-	5.6	-	-	4.0
ESDB08A	AD1870	AD1977	ESDB-12																	3.6	4.3	-	-	\	-	-	-	-	-	-	-	-	4.1	3.6	-	-
ESDB09	AD1799	AD1999	ESDB-12																		6.3	6.0	4.6	4.5	-	-	-	-	-	-	-	-	4.0	-	-	-
ESDB11	AD1820	AD2005	ESDB-12																			6.0	-	3.8	4.2	-	-	-	-	6.5	-	3.5	5.2	4.9	5.4	-
ESDB12A	AD1860	AD2005	ESDB-12																				-	-	-	-	-	-	-	-	-	-	-	-	-	-
ESDB13	AD1936	AD2005	ESDB-12																					5.9	-	-	\	-	\	-	\	-	-	-	-	-
ESDG01	AD1965	AD2005	ESDG-13																						\	5.2	\	-	\	6.1	\	\	3.6	\	4.5	-
ESDG02	AD1862	AD1953	ESDG-13																							-	5.5	4.7	3.8	5.8	-	7.9	6.0	5.0	6.1	-
ESDG03	AD1855	AD2005	ESDG-13																								-	-	-	4.4	-	-	-	-	3.9	-
ESDG04	AD1874	AD1941	ESDG-13																									7.1	5.9	6.1	-	5.4	6.2	4.9	5.6	-
ESDG05	AD1896	AD2005	ESDG-13																										6.1	3.6	-	8.3	-	6.3	5.3	-
ESDG06	AD1886	AD1945	ESDG-13																											-	-	5.6	4.3	-	4.7	-
ESDG07	AD1882	AD2005	ESDG-13																												-	8.3	11.3	4.7	7.9	5.5
ESDG08	AD1865	AD1938	ESDG-13																													5.0	3.6	3.8	6.1	-
ESDG09	AD1871	AD1969	ESDG-13																														6.9	5.1	7.4	-
ESDG10	AD1854	AD2003	ESDG-13																															6.6	6.8	-
ESDG11	AD1856	AD1972	ESDG-13																																7.6	-
ESDG12	AD1878	AD2005	ESDG-13																																	-
ESDG13A	AD1837	AD1990	ESDG-13																																	

KEY: \ = overlap < 15 years, - = t-values less than 3.50.

🟨 = samples from peat

Statistics:
ESBE-09, n = 31, min t = -0.80, max t = 8.19, mean t = 3.83, SD = 2.11
ESDG-13, n = 72, min t = -0.50, max t = 11.26, mean t = 4.21, SD = 2.43
ESDB-12, n = 66, min t = 1.77, max t = 8.72, mean t = 4.55, SD = 1.58

Table 38: Cross-matching between series from Glen Affric

Filenames	Start date	End date	Chronology name	38702	38703	38704	38705	38806	38807	38808	38809	38810	38911	38912	38913
38701	AD1735	AD1976	GLNAFRIC	4.8	-	5.0	5.0	5.5	6.3	-	4.0	3.9	-	6.1	4.3
38702	AD1766	AD1976	GLNAFRIC		4.7	5.5	5.5	4.2	4.2	4.6	5.2	6.8	-	5.4	3.9
38703	AD1808	AD1976	GLNAFRIC			-	-	-	-	4.9	3.7	4.4	-	-	-
38704	AD1766	AD1976	GLNAFRIC				4.8	8.5	3.9	-	-	3.6	4.5	5.0	5.2
38705	AD1808	AD1976	GLNAFRIC					-	5.7	4.7	5.3	-	5.4	7.8	5.3
38806	AD1816	AD1976	GLNAFRIC						4.9	-	3.7	-	3.7	-	4.7
38807	AD1785	AD1976	GLNAFRIC							-	5.3	3.6	4.3	5.5	4.2
38808	AD1810	AD1976	GLNAFRIC								4.2	4.4	-	3.7	-
38809	AD1827	AD1976	GLNAFRIC									4.4	4.3	-	3.5
38810	AD1776	AD1976	GLNAFRIC										-	4.2	3.8
38911	AD1758	AD1976	GLNAFRIC											5.3	3.6
38912	AD1840	AD1976	GLNAFRIC												7.6
38913	AD1769	AD1976	GLNAFRIC												

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: GLNAFRIC, n = 78 min t = 1.04 max t = 8.48 mean t = 4.12 SD = 1.48

Table 39: Cross-matching between series from Glen Derry

Filenames	Start date	End date	Chronology name	56811	56812	56901	56902	56903	56904	56905	56906	56907	56908	56909	57213
56810	AD1808	AD1978	GLNDERRY	8.8	5.3	-	4.4	5.6	5.3	6.4	6.9	4.8	5.0	5.2	5.2
56811	AD1773	AD1978	GLNDERRY		6.7	5.1	7.3	7.4	7.1	7.6	8.7	8.2	6.4	8.7	8.8
56812	AD1801	AD1978	GLNDERRY			5.4	4.6	4.0	6.3	7.3	5.1	5.6	5.8	9.0	6.1
56901	AD1773	AD1978	GLNDERRY				3.6	4.1	7.9	4.5	7.5	5.4	5.4	8.3	4.8
56902	AD1779	AD1978	GLNDERRY					7.8	6.5	5.2	6.6	10.2	8.5	7.5	7.3
56903	AD1779	AD1978	GLNDERRY						7.8	7.4	6.7	8.6	6.9	6.0	4.6
56904	AD1820	AD1978	GLNDERRY							6.2	7.5	8.0	6.1	6.9	5.7
56905	AD1784	AD1978	GLNDERRY								6.3	5.5	6.8	6.8	6.0
56906	AD1796	AD1978	GLNDERRY									9.4	6.8	7.2	7.4
56907	AD1790	AD1978	GLNDERRY										7.6	8.2	7.9
56908	AD1810	AD1978	GLNDERRY											7.8	6.9
56909	AD1833	AD1978	GLNDERRY												8.1
57213	AD1856	AD1978	GLNDERRY												

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: GLNDERRY, n = 78 min t = 3.16 max t = 10.24 mean t = 6.60 SD = 1.46

Table 40: Cross-matching between series from Inshriach

Filenames	Start Date	End Date	Chronology name	52	53	59	60
INSH51	AD1953	AD1999	INSH-M1	-	-	4.1	3.8
INSH52	AD1953	AD1999	INSH-M1	*	3.6	-	4.1
INSH53	AD1954	AD1999	INSH-M1	*	*	-	-
INSH59	AD1960	AD1999	INSH-M2	*	*	*	4.0
INSH60	AD1958	AD1999	INSH-M2	*	*	*	*

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
🟨 = samples from peat
Statistics: INSH-M1, n = 3, min t = 1.02, max t = 3.63, mean t = 2.66, SD = 1.17
INSH-M2, t = 3.99

Table 41: Cross-matching between series from Inverey

Filenames	Start date	End date	Chronology name	38002	38003	38004A	38004B	38105	38106	38107	38108	38109	38210	38211	38212
38001	AD1717	AD1976	INVEREY	6.9	5.3	4.2	4.2	9.0	5.9	6.4	7.6	8.7	5.8	5.2	8.1
38002	AD1706	AD1976	INVEREY		5.1	4.7	-	6.4	3.8	6.5	6.7	7.3	5.2	4.6	4.9
38003	AD1754	AD1976	INVEREY			6.1	5.3	6.8	5.5	6.6	6.9	5.9	7.3	5.1	6.4
38004A	AD1754	AD1873	INVEREY				\	4.9	3.7	5.2	5.6	5.5	4.6	-	3.6
38004B	AD1893	AD1976	INVEREY					4.7	-	4.3	6.0	6.0	5.2	-	5.6
38105	AD1731	AD1976	INVEREY						7.3	8.5	10.0	9.3	9.3	6.9	13.9
38106	AD1750	AD1976	INVEREY							7.9	6.1	7.2	4.3	5.4	6.9
38107	AD1754	AD1976	INVEREY								11.0	6.6	7.7	7.2	9.1
38108	AD1721	AD1976	INVEREY									10.7	9.1	6.8	9.0
38109	AD1724	AD1976	INVEREY										9.0	7.8	7.9
38210	AD1716	AD1976	INVEREY											9.0	10.0
38211	AD1769	AD1976	INVEREY												7.0
38212	AD1783	AD1976	INVEREY												

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: INVEREY, n = 77 min t = 2.88 max t = 13.94 mean t = 6.53 SD = 2.05

Table 42: Cross-matching between series from Loch Maree

Filenames	Start date	End date	Chronology name	57202	57203	57204	57205	57206	57207	57209
57201	AD1771	AD1978	LCHMAREE	-	3.8	7.3	-	7.3	4.5	6.0
57202	AD1885	AD1978	LCHMAREE		-	-	-	-	-	-
57203	AD1845	AD1978	LCHMAREE			4.2	4.1	-	4.7	4.7
57204	AD1834	AD1978	LCHMAREE				5.3	5.0	4.7	5.7
57205	AD1812	AD1978	LCHMAREE					-	-	-
57206	AD1765	AD1978	LCHMAREE						5.0	5.4
57207	AD1822	AD1978	LCHMAREE							5.8
57209	AD1756	AD1978	LCHMAREE							

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: LCHMAREE, n = 28 min t = 1.07 max t = 7.27 mean t = 3.94 SD = 1.74

Table 43: Cross-matching between series from Mallaig

Filenames	Start date	End date	Chronology name	39203	39205	39206	39307	39308	39309	39310	39411	39412
39201	AD1917	AD1976	MALLAIG	5.5	-	-	-	-	-	5.7	3.9	-
39203	AD1921	AD1976	MALLAIG		7.0	7.3	5.1	5.2	-	6.1	4.1	4.4
39205	AD1928	AD1976	MALLAIG			6.0	-	6.9	-	4.5	-	-
39206	AD1920	AD1976	MALLAIG				3.7	4.9	-	5.4	3.6	-
39307	AD1921	AD1976	MALLAIG					3.6	-	-	-	-
39308	AD1904	AD1976	MALLAIG						-	-	-	3.9
39309	AD1916	AD1976	MALLAIG							-	4.4	-
39310	AD1903	AD1976	MALLAIG								4.3	-
39411	AD1931	AD1976	MALLAIG									-
39412	AD1911	AD1972	MALLAIG									

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: MALLAIG, n = 45 min t = 1.03 max t = 7.26 mean t = 3.61 SD = 1.62

Table 44: Cross-matching between series from Monadh Mor

Filenames	Start Date	End Date	Chronology name	51	54	55	56	60	40	52	53	59
MONM01	AD1912	AD1999	MONM-M1	5.0	5.4	5.4	-	3.7	-	-	-	-
MONM51	AD1922	AD1999	MONM-M1		3.8	4.4	-	3.5	-	-	-	-
MONM54	AD1912	AD1999	MONM-M1			4.0	-	4.5	-	-	-	-
MONM55	AD1920	AD1999	MONM-M1				4.0	-	-	-	-	-
MONM56	AD1906	AD1999	MONM-M1					-	-	-	-	-
MONM60	AD1912	AD1999	MONM-M1						-	-	-	-
MONM40	AD1934	AD1999	MONM-M2							5.0	3.5	4.9
MONM52	AD1944	AD1999	MONM-M2								3.5	-
MONM53	AD1935	AD1999	MONM-M2									-
MONM59	AD1943	AD1999	MONM-M2									

KEY: \ = overlap < 15 years, - = t-values less than 3.50. 🟨 = samples from peat

Statistics: MONM-M1, n = 21, min t = 1.18, max t = 6.30, mean t = 3.33, SD = 1.34
MONM-M2, n = 6, min t = 2.55, max t = 5.04, mean t = 3.82, SD = 0.88

Notes: MONM55 matches with a t-value of 6.3 against a mean of the other 5 sequences
MONM59 matches with a t-value of 5.0 against a mean of the other 3 sequences

Table 45: Cross-matching between series from Pitmaduthy Moss

File Names	Start date	End date	Chronology name	52A	53A	56A	60	61-2	63A	64	65A	66A	67	68A	01A	03A	06A	07A	08	09A
PITM51A	AD1884	AD1999	PITM-M1	4.9	6.3	6.0	6.1	-	6.2	4.2	4.9	7.3	4.2	6.5	-	-	-	-	-	-
PITM52A	AD1898	AD1999	PITM-M1		6.1	7.2	5.5	-	5.4	3.6	5.9	5.3	5.8	6.6	-	-	-	-	-	-
PITM53A	AD1902	AD1999	PITM-M1			8.8	6.2	-	6.6	4.4	7.4	6.3	4.0	6.6	-	-	-	-	-	-
PITM56A	AD1897	AD1999	PITM-M1				6.7	-	7.1	-	8.6	8.8	4.6	7.6	-	-	-	-	-	-
PITM60	AD1912	AD1999	PITM-M1					-	9.5	5.3	6.9	6.0	6.4	9.0	4.6	-	-	-	-	-
PITM61-2	AD1920	AD1999	PITM-M1						4.3	4.4	4.2	4.9	4.0	5.6	3.6	-	3.9	-	4.2	-
PITM63A	AD1894	AD1999	PITM-M1							5.6	6.3	11.0	5.1	8.6	-	-	4.1	-	-	-
PITM64	AD1923	AD1999	PITM-M1								-	3.7	-	4.0	-	-	-	-	-	-
PITM65A	AD1897	AD1999	PITM-M1									7.1	4.4	6.5	-	-	-	-	-	-
PITM66A	AD1875	AD1999	PITM-M1										4.4	7.0	-	-	-	-	-	-
PITM67	AD1898	AD1937	PITM-M1											6.2	\	\	\	\	\	\
PITM68A	AD1901	AD1999	PITM-M1												3.5	-	-	-	-	-
PITM01A	AD1938	AD1999	PITM-M2													-	4.9	3.8	-	5.6
PITM03A	AD1939	AD1999	PITM-M2														3.6	-	4.1	-
PITM06A	AD1949	AD1999	PITM-M2															4.6	7.3	7.3
PITM07A	AD1941	AD1999	PITM-M2																4.6	4.4
PITM08	AD1938	AD1999	PITM-M2																	5.6
PITM09A	AD1941	AD1991	PITM-M2																	

KEY: \ = overlap < 15 years, - = t-values less than 3.50. 🟨 = samples from peat

Statistics: PITM-M1, n = 66, min t = 2.14, max t = 10.96, mean t = 5.68, SD = 1.80
PITM-M2, n = 15, min t = 1.87, max t = 7.31, mean t = 4.44, SD = 1.49

Table 46: Cross-matching between series from Plockton

Filenames	Start date	End date	Chronology name	39002	39003	39004	39005	39006	39108	39109	39110	39111	39112	39113
39001	AD1887	AD1976	PLOCKTON	4.5	3.9	5.4	4.3	-	6.7	4.5	3.7	5.7	4.2	5.7
39002	AD1900	AD1976	PLOCKTON		-	4.1	-	-	-	5.0	-	-	-	-
39003	AD1894	AD1976	PLOCKTON			-	4.6	-	4.2	-	3.8	5.2	-	-
39004	AD1909	AD1976	PLOCKTON				4.0	-	3.6	-	-	-	-	4.1
39005	AD1885	AD1976	PLOCKTON					-	4.0	3.5	-	-	-	4.9
39006	AD1904	AD1976	PLOCKTON						3.7	4.6	-	-	-	-
39108	AD1886	AD1976	PLOCKTON							4.2	-	7.9	-	4.6
39109	AD1899	AD1976	PLOCKTON								4.9	-	4.2	3.7
39110	AD1885	AD1976	PLOCKTON									-	4.1	-
39111	AD1879	AD1976	PLOCKTON										3.7	5.8
39112	AD1904	AD1976	PLOCKTON											4.2
39113	AD1881	AD1976	PLOCKTON											

KEY: \ = overlap < 15 years, - = t-values less than 3.50.

Statistics: PLOCKTON, n = 66 min t = 0.79 max t = 7.88 mean t = 3.60 SD = 1.28

Table 47: Cross-matching between series from Shieldaig

Filenames	Start date	End date	Chronology name	57102	57103	57104	57105	57106	57107	57108	57109	57110	57111
57101	AD1899	AD1978	SHIELDAIG	-	-	-	4.5	-	3.7	-	-	-	3.6
57102	AD1860	AD1978	SHIELDAIG		4.7	4.0	5.6	-	3.7	4.4	5.0	5.3	5.9
57103	AD1847	AD1978	SHIELDAIG			6.3	-	-	4.3	3.6	4.3	3.6	6.3
57104	AD1864	AD1978	SHIELDAIG				-	5.2	5.1	-	-	4.2	6.6
57105	AD1859	AD1978	SHIELDAIG					-	4.1	-	-	-	5.1
57106	AD1883	AD1978	SHIELDAIG						3.6	-	-	4.2	4.0
57107	AD1873	AD1967	SHIELDAIG							4.2	5.1	3.9	5.9
57108	AD1853	AD1978	SHIELDAIG								7.5	4.4	5.0
57109	AD1866	AD1978	SHIELDAIG									5.8	6.0
57110	AD1877	AD1976	SHIELDAIG										5.3
57111	AD1856	AD1978	SHIELDAIG										

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: SHIELDAIG, n = 55 min t = 2.00 max t = 7.53 mean t = 4.10 SD = 1.30

Table 48: Cross-matching between series from Strathnaver

Filenames	Start date	End date	Chronology name	04	06	07A	08	09	10A	03	04	06A	07	08	09
STIN02	AD1969	AD2005	STIN-07	-	3.9	4.0	-	4.8	-	-	-	-	3.6	-	-
STIN04	AD1967	AD2005	STIN-07		4.4	-	4.9	-	3.6	4.1	4.0	-	4.4	4.7	-
STIN06	AD1966	AD1996	STIN-07			4.9	3.9	3.9	-	-	-	-	3.6	-	-
STIN07A	AD1966	AD2005	STIN-07				-	6.3	-	-	-	-	-	-	-
STIN08	AD1966	AD2005	STIN-07					-	4.1	-	3.9	-	-	-	-
STIN09	AD1968	AD2001	STIN-07						-	-	-	-	-	-	-
STIN10A	AD1969	AD2005	STIN-07							-	-	-	-	-	-
STWB03	AD1966	AD2005	STPE-10								5.9	4.9	4.7	3.6	-
STWB04	AD1971	AD2005	STPE-10									4.8	5.5	4.4	3.8
STWB06A	AD1975	AD2005	STPE-10										5.6	-	4.6
STWB07	AD1974	AD2005	STPE-10											4.4	3.7
STWB08	AD1971	AD2003	STPE-10												-
STWB09	AD1965	AD2005	STPE-10												

KEY: \ = overlap < 15 years, - = t-values less than 3.50.
Statistics: STIN-07, n = 21, min t = 1.18, max t = 6.30, mean t = 3.33, SD = 1.34
STWB-06, n = 15, min t = 2.38, max t = 5.90, mean t = 4.25, SD = 1.02

Table 49: Cross-matching between series from Loch Ascaig – A

Filenames	Start Date	End Date	Chronology name	02	08
ASCA01	11	184	ASCA-A	5.5	5.6
ASCA02	10	92	ASCA-A		5.5
ASCA08	1	100	ASCA-A		

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: ASCA-A, n = 3, min t = 5.50, max t = 5.60, mean t = 5.54, SD = 0.04

Table 50: Cross-matching between series from Loch Ascaig – B

Filenames	Start Date	End Date	Chronology name	05	06
ASCA04	1	190	ASCA-B	5.4	6.3
ASCA05	7	175	ASCA-B		3.8
ASCA06	7	105	ASCA-B		

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: ASCA-B, n = 3, min t = 3.83, max t = 6.30, mean t = 5.16, SD = 1.02

Table 51: Cross-matching between series from Loch Assynt

Filenames	Start Date	End Date	Chronology name	03	05	09
ASSA01	110	252	ASSA-4	5.9	-	-
ASSA03	38	257	ASSA-4		3.7	-
ASSA05	34	193	ASSA-4			4.3
ASSA09	1	145	ASSA-4			

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: ASSA-4, n = 6, min t = -0.17, max t = 5.88, mean t = 3.26, SD = 1.86

Table 52: Cross-matching between series from Druim Bad a' Ghaill – A

Filenames	Start Date	End Date	Chronology name	06	07	09	17	18	20	21	23	27A	28	29
BADA05	1	115	BADA-12	-	3.7	3.6	4.2	3.6	-	5.5	-	4.5	7.0	4.4
BADA06	12	138	BADA-12		-	-	-	-	3.8	6.3	3.9	4.7	4.1	-
BADA07	18	105	BADA-12			-	-	-	-	4.3	4.1	-	4.0	-
BADA09	51	186	BADA-12				5.8	6.8	4.9	-	-	-	5.2	5.7
BADA17	39	179	BADA-12					-	5.7	4.8	4.4	5.4	7.4	7.7
BADA18	32	173	BADA-12						-	-	-	-	4.3	6.1
BADA20	29	142	BADA-12							5.6	4.1	5.5	6.8	-
BADA21	21	125	BADA-12								8.7	4.8	7.6	3.6
BADA23	1	105	BADA-12									4.4	5.5	-
BADA27A	21	121	BADA-12										4.2	-
BADA28	6	142	BADA-12											5.2
BADA29	38	159	BADA-12											

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: BADA-12, n = 66, min t = 1.19, max t = 8.65, mean t = 4.10, SD = 1.73

Table 53: Cross-matching between series from Druim Bad a' Ghaill – B

Filenames	Start Date	End Date	Chronology name	08	10	11	14	15
BADA01	1	65	BADA-B	4.3	4.4	5.4	4.4	4.5
BADA08	6	79	BADA-B		5.1	6.9	5.1	3.9
BADA10	8	72	BADA-B			6.5	-	6.0
BADA11	3	76	BADA-B				6.3	6.7
BADA14	4	52	BADA-B					4.4
BADA15	4	112	BADA-B					

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: BADA-B, n = 15, min t = 2.89, max t = 6.90, mean t = 5.12, SD = 1.12

Table 54: Cross-matching between series from Druim Bad a’ Ghaill – C

Filenames	Start Date	End Date	Chronology name	16	19
BADA12	1	74	BADA-C	3.8	5.1
BADA16	18	102	BADA-C		5.1
BADA19	7	74	BADA-C		

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: BADA-C, n = 3, min t = 3.84, max t = 5.06, mean t = 4.65, SD = 0.57

Table 55: Cross-matching between series from An Dubh-loch

Filenames	Start Date	End Date	Chronology name	02	03
DUBH01	3	90	DUBH-3	5.0	6.7
DUBH02	1	67	DUBH-3		4.0
DUBH03	7	93	DUBH-3		

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: DUBH-3, n = 3, min t = 4.01, max t = 6.72, mean t = 5.24, SD = 1.12

Table 56: Cross-matching between series from Polla at Loch Eriboll

Filenames	Start Date	End Date	Chronology name	06	07	09A	10	11
POLL05	35	344	POLL-6	9.5	5.0	6.3	4.9	4.9
POLL06	13	289	POLL-6		-	-	4.3	5.8
POLL07	1	172	POLL-6			4.1	6.0	-
POLL09A	18	185	POLL-6				5.8	5.4
POLL10	15	293	POLL-6					4.0
POLL11	34	214	POLL-6					

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: POLL-6, n = 15, min t = -0.01, max t = 9.47, mean t = 4.69, s.d. = 2.09

Table 57: Cross-matching between series from Loch an Rathair

Filenames	Start Date	End Date	Chronology name	02	03	07A	08	10	12	17
RATH01	71	199	RATH-8	-	3.9	-	3.6	-	3.6	-
RATH02	59	231	RATH-8		5.3	3.8	3.5	-	3.6	-
RATH03	136	232	RATH-8			-	4.6	3.6	3.6	-
RATH07A	1	152	RATH-8				6.0	-	4.9	-
RATH08	58	228	RATH-8					-	6.8	3.6
RATH10	76	213	RATH-8						4.8	4.8
RATH12	60	221	RATH-8							4.6
RATH17	10	174	RATH-8							

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: RATH-8, n = 28 min, t = 0.96, max t = 6.76, mean t = 3.62, SD = 1.27

Table 58: Cross-matching between series from Skerricha

Filenames	Start Date	End Date	Chronology name	06	08	09	11A	12	13
SKER05	37	107	SKER-7	6.1	4.6	4.5	5.8	5.4	5.1
SKER06	23	92	SKER-7		5.2	5.6	4.4	3.6	3.9
SKER08	4	142	SKER-7			4.2	5.2	5.0	4.8
SKER09	2	92	SKER-7				3.6	5.1	3.7
SKER11A	56	127	SKER-7					3.8	3.5
SKER12	1	103	SKER-7						5.4
SKER13	5	161	SKER-7						

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: SKER-7, n = 21, min t = 3.52, max t = 6.08, mean t = 4.69, SD = 0.77

Table 59: Cross-matching between series from Strath Canaird

Filenames	Start Date	End Date	Chronology name	12	13	14	17	18	20	21	23	29	30	31	32
SMUR10	77	292	SMUR-13	-	-	4.1	-	-	5.0	-	5.8	-	4.3	5.7	-
SMUR12	72	142	SMUR-13		-	-	-	-	-	-	-	4.1	-	5.2	-
SMUR13	9	147	SMUR-13			4.4	4.0	4.4	4.4	4.5	-	-	-	-	-
SMUR14	13	222	SMUR-13				-	-	8.4	4.6	5.3	4.6	-	8.2	-
SMUR17	14	120	SMUR-13					3.7	-	4.5	-	3.9	-	-	3.8
SMUR18	14	119	SMUR-13						-	4.5	-	6.1	-	3.6	5.0
SMUR20	51	292	SMUR-13							6.2	4.8	4.2	4.1	8.0	-
SMUR21	11	231	SMUR-13								-	4.5	-	5.2	4.4
SMUR23	69	308	SMUR-13									-	-	5.5	-
SMUR29	9	216	SMUR-13										-	7.4	5.8
SMUR30	68	308	SMUR-13											3.8	4.2
SMUR31	69	270	SMUR-13												-
SMUR32	1	159	SMUR-13												

KEY: \ = overlap < 15 years, - = t-values less than 3.50
Statistics: SMUR-13 ,n = 78 min, t = -0.16, max t = 8.39, mean t = 3.43, SD = 1.88

7.4 Appendix IV: Bar diagrams and pith information

Key: C = pith, V = within 5 years of pith, F = within 10 years of pith.

Figure 105: Bar diagram highlighting the age structure and main recruitment phases of pine sampled from four sites at Abernethy.

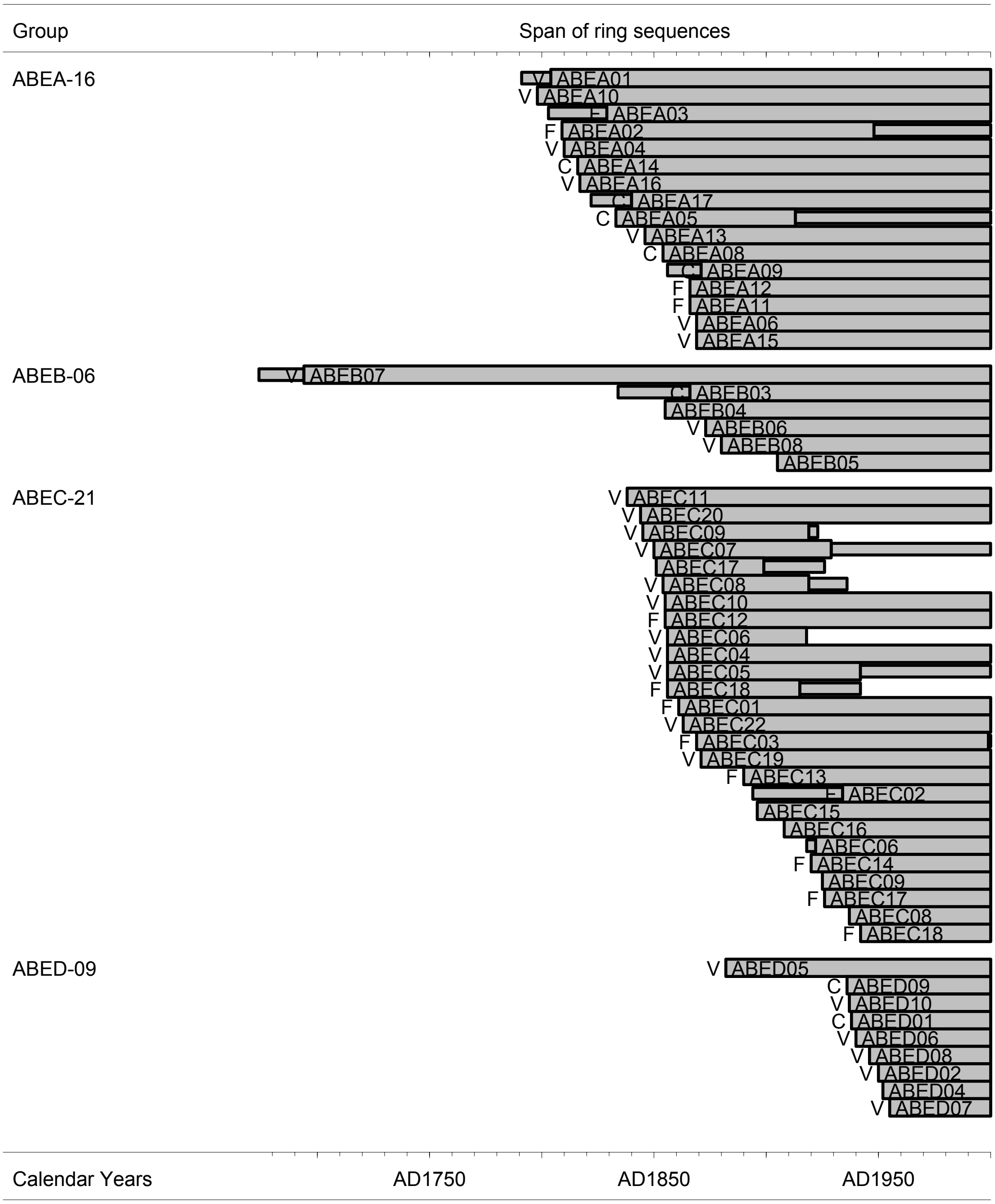


Figure 106: Bar diagram highlighting the age structure and main recruitment phases of pine sampled from Achanalt, Ballochbuie, Beinn Eighe and Borgie Forest

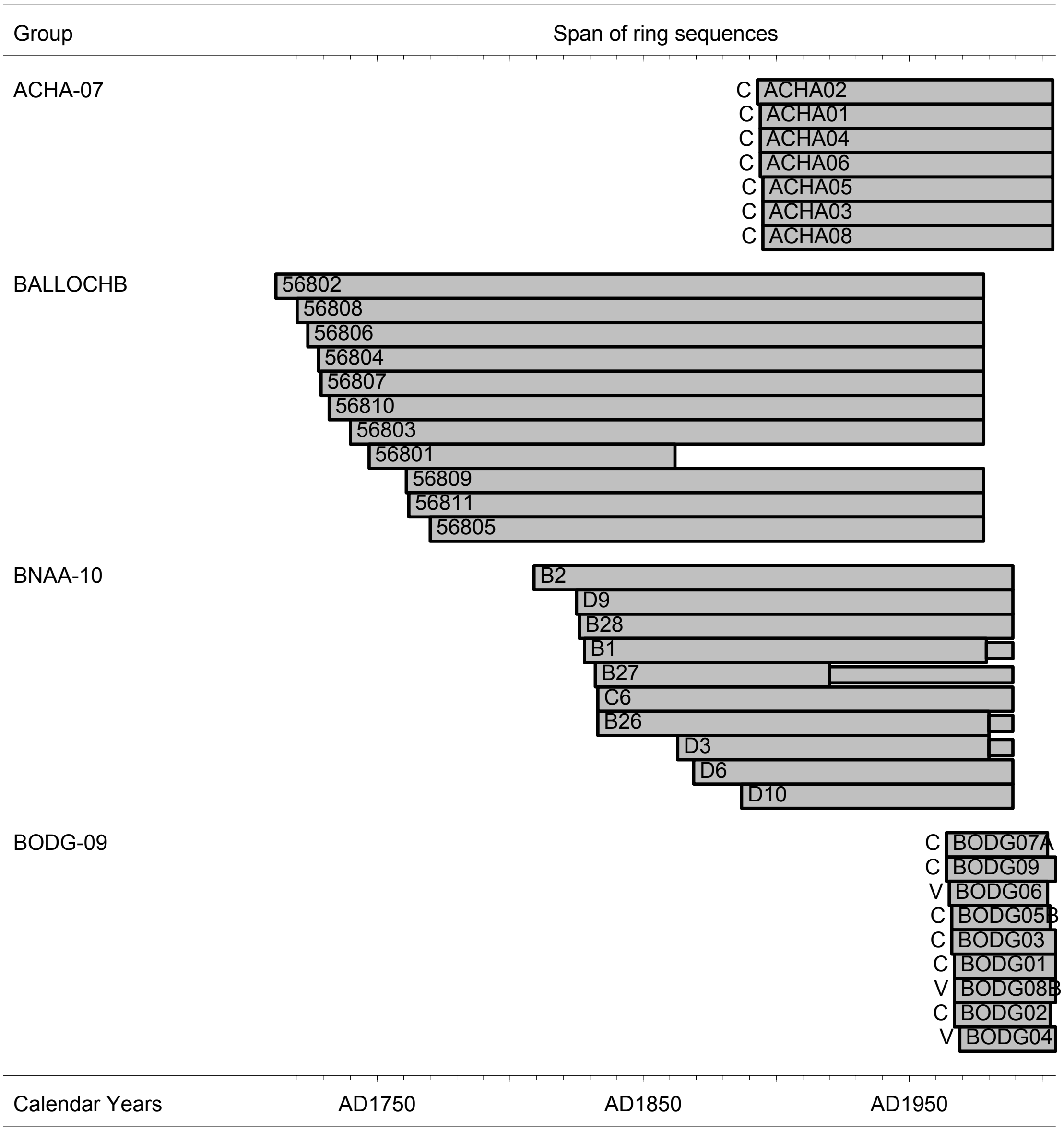


Figure 107: Bar diagram highlighting the age structure and main recruitment phases of pine sampled from Coulin, Dimme, and three sites at Eilann Sùbhainn.

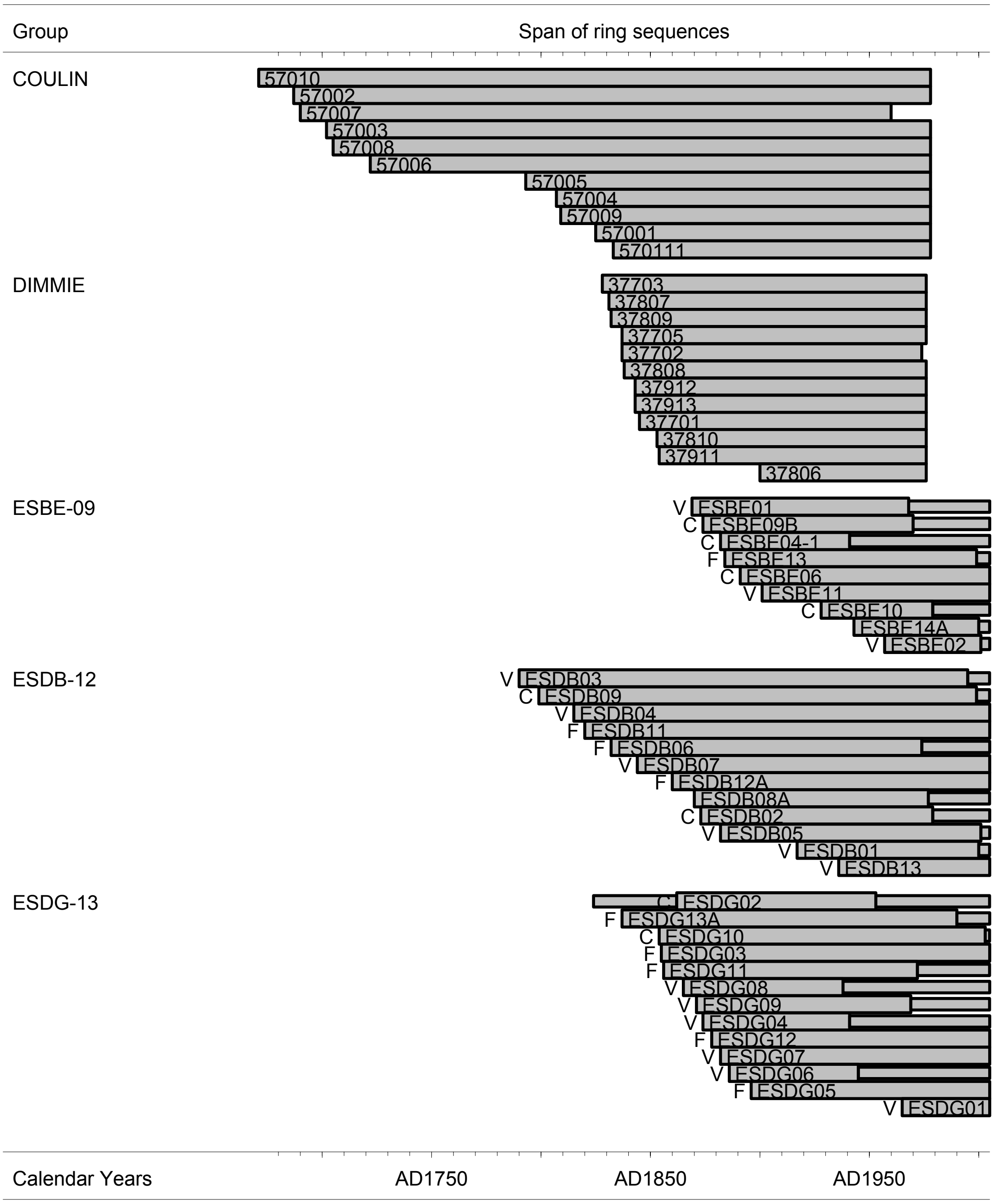


Figure 108: Bar diagram highlighting the age structure and main recruitment phases of pine sampled from Glen Afric, Inshriach, Inverey and Loch Maree.

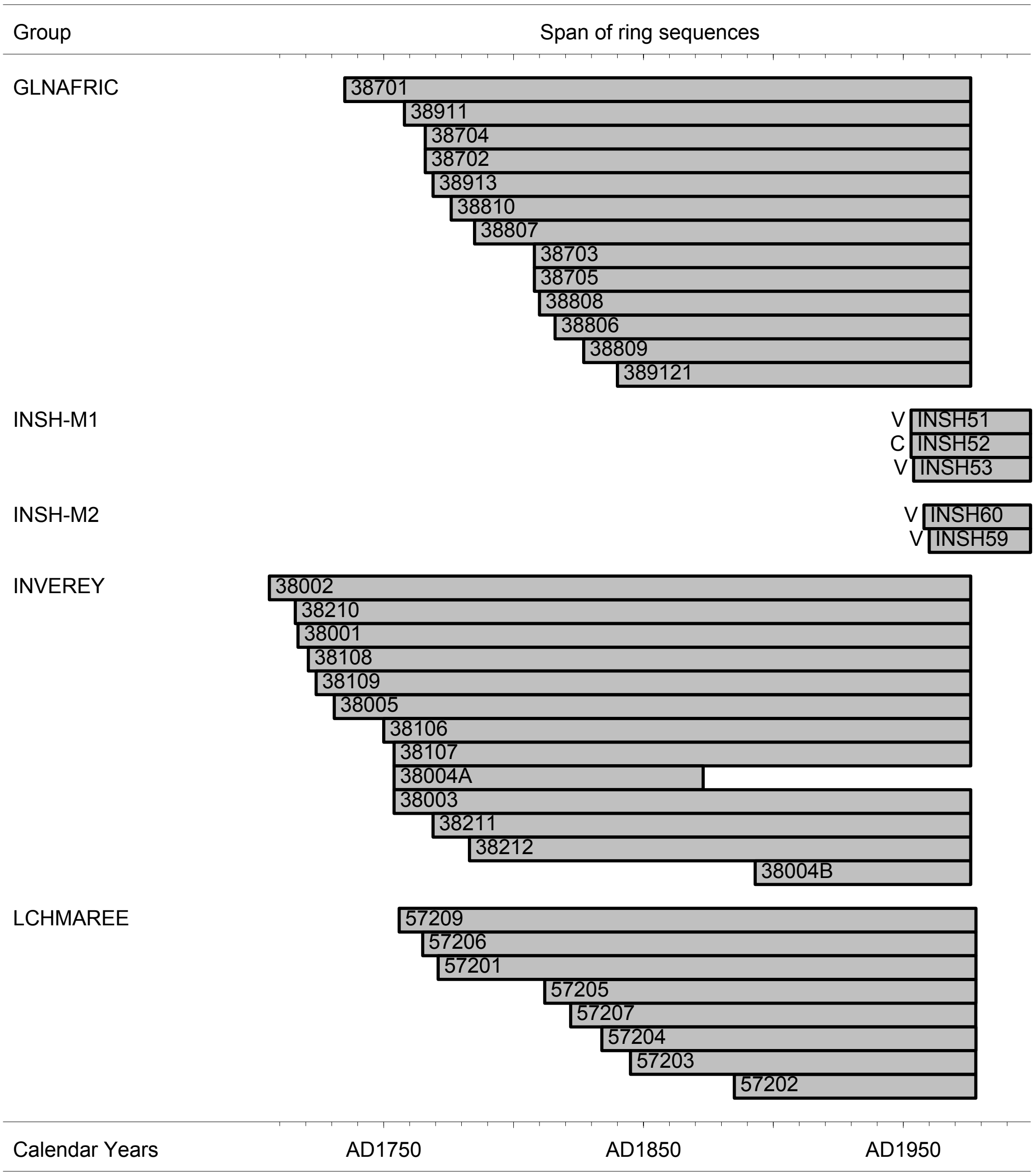


Figure 109: Bar diagram highlighting the age structure and main recruitment phases of pine sampled from Mallaig, Monada Mor and the Naver Forest.

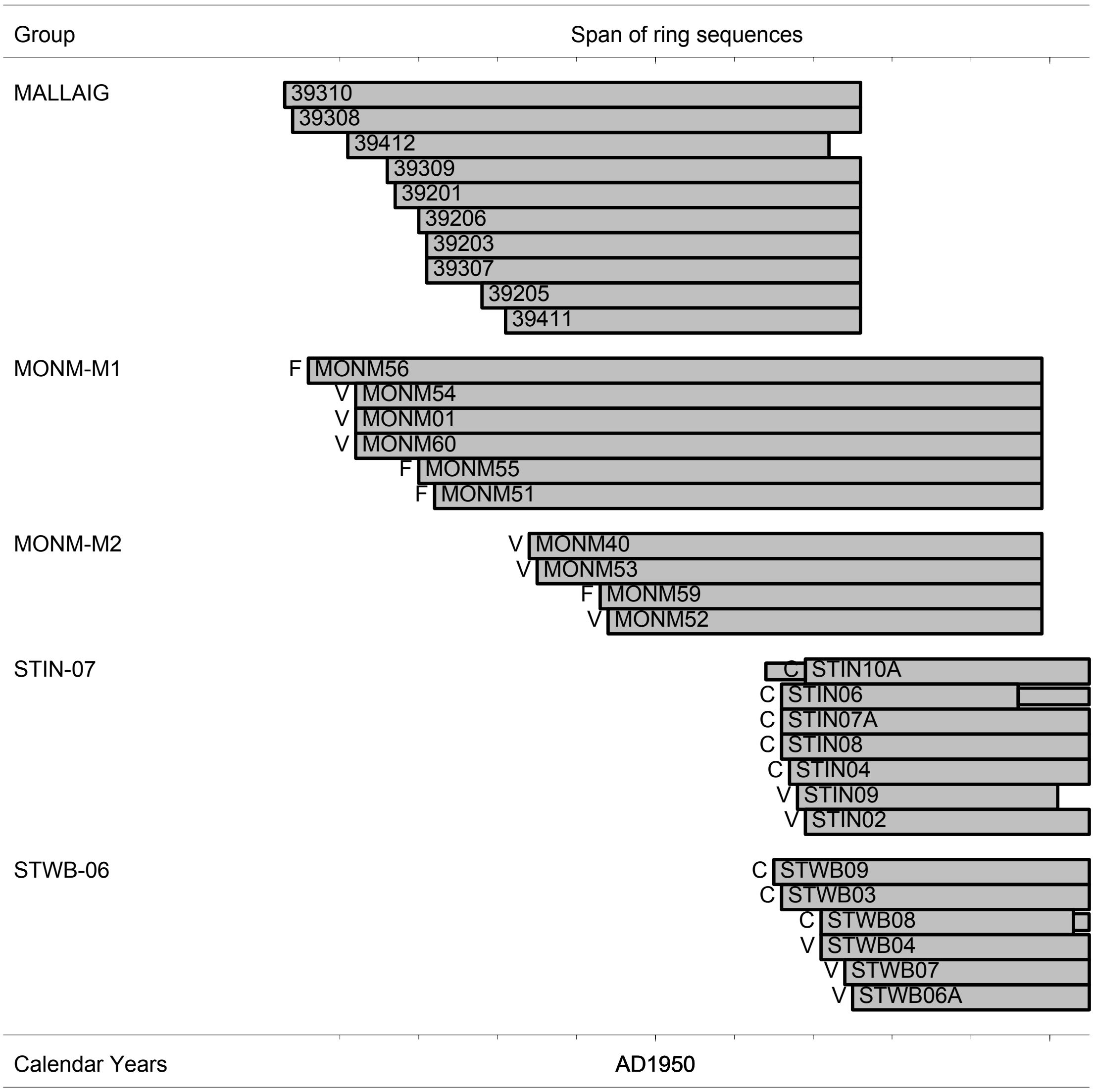
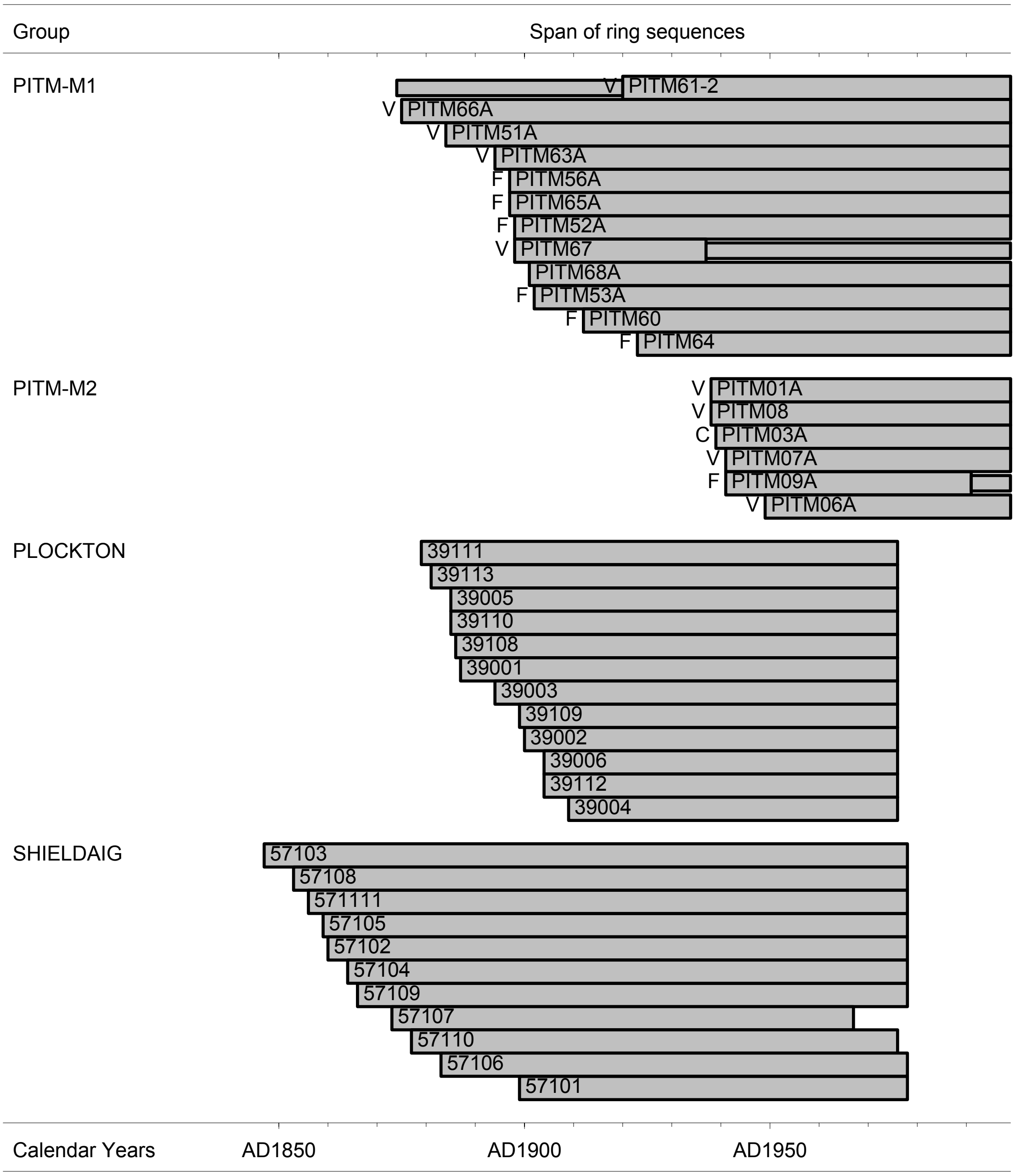
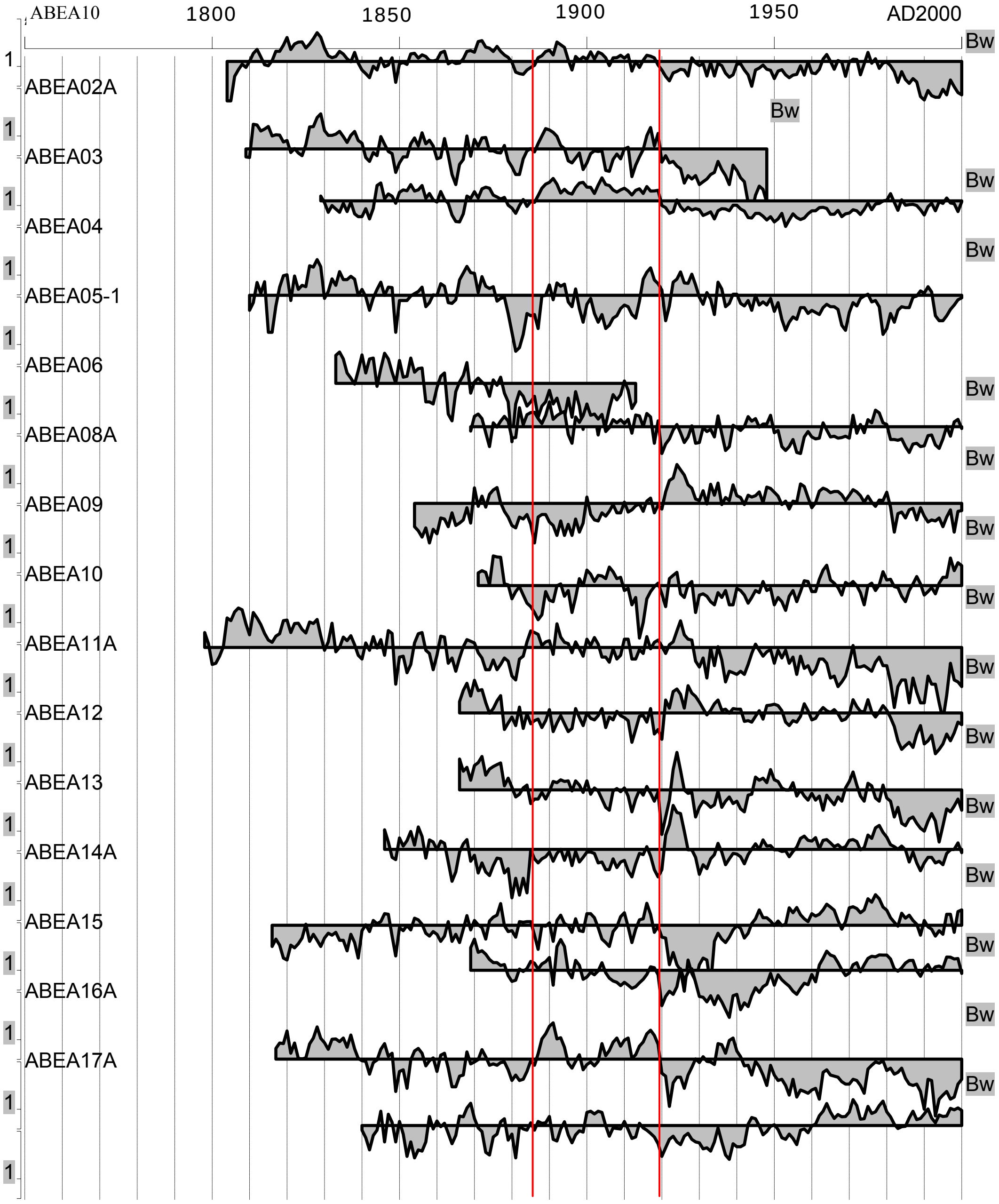


Figure 110: Bar diagram highlighting the age structure and main recruitment phases of pine sampled from Pitmaduthy, Plockton and Shieldaig.



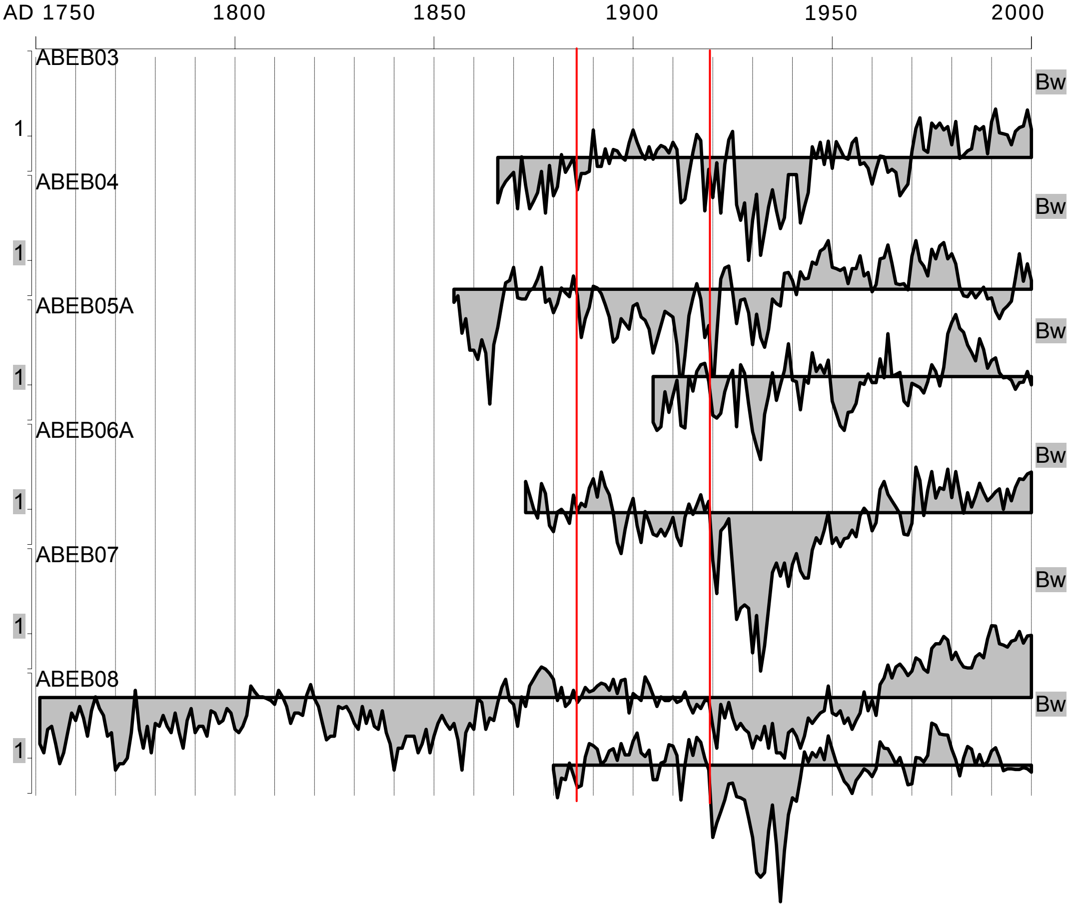
7.5 Appendix V: Plots of modern tree-ring series

Figure 111: Tree-ring series from Abernethy (site A) - showing 20-40 year out-of-phase fluctuations between the ring-width of different trees.



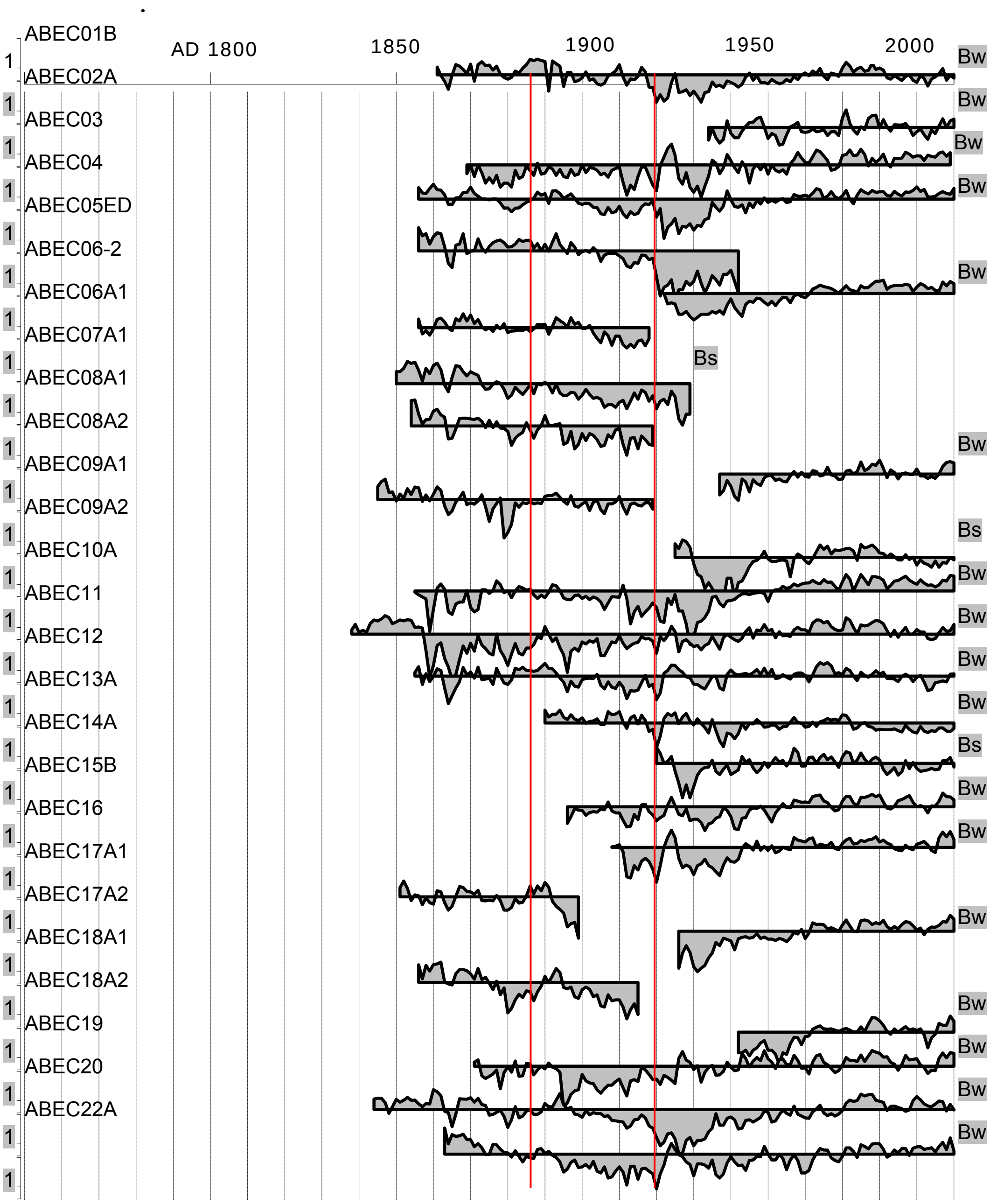
Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicate firescars in *c.* 1887, AD 1920, Bw = Winter bark

Figure 112: Tree-ring series from Abernethy (site B) - showing generally common growth trends between trees.



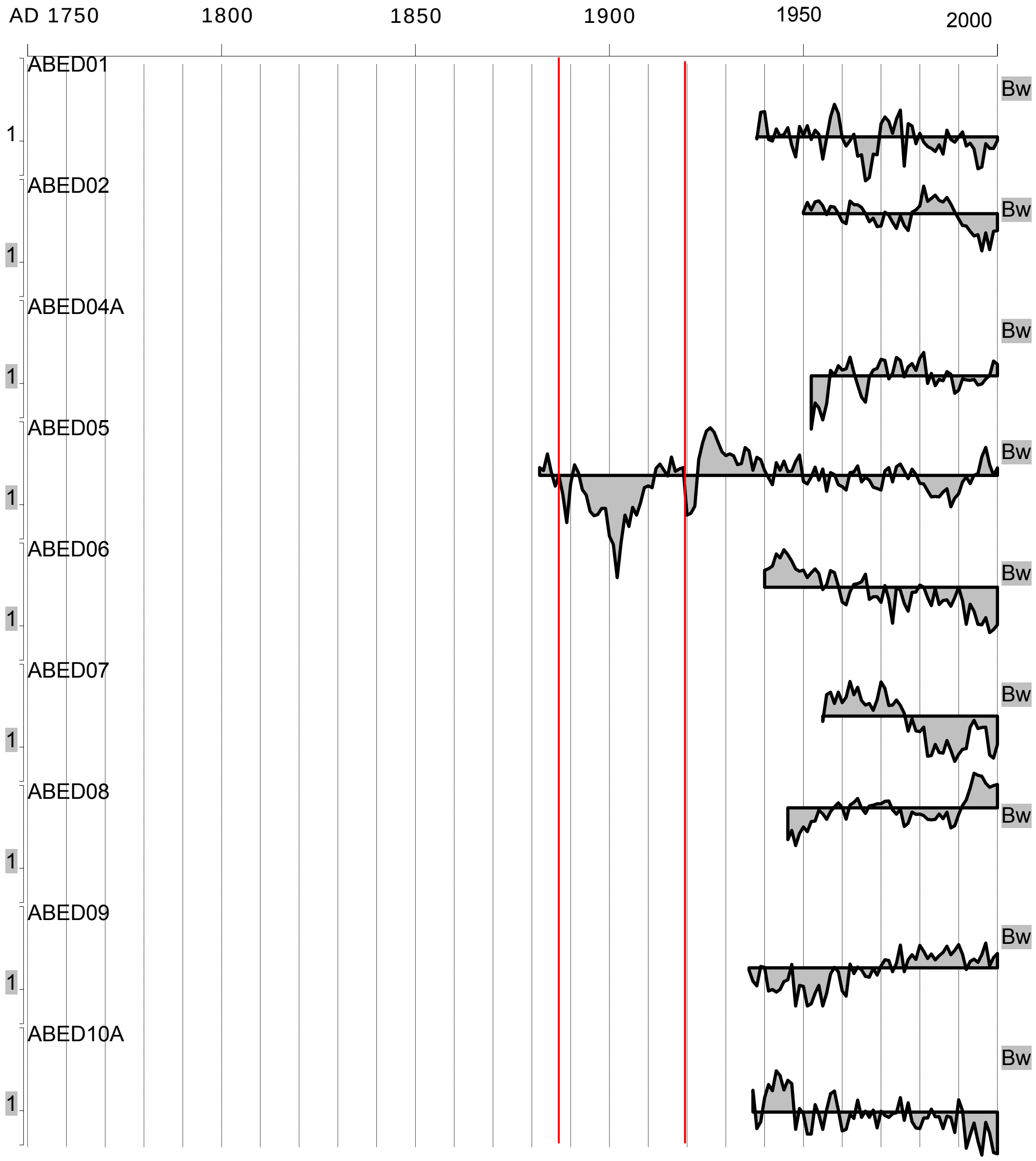
Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicate firescars identified from Abernethy (site A) in *c.* 1887, AD 1920, Bw = Winter bark

Figure 113: Tree-ring series from Abernethy (site C) - showing 10-30 year out-of-phase fluctuations between the ring-width of different trees.



Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicate firescars identified from Abernethy (site A) in *c.* 1887, AD 1920, Bw = Winter bark

Figure 114: Tree-ring series from Abernethy (site D) showing 10-20 year out-of-phase fluctuations between the ring-width of different trees



Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicate firescars identified from Abernethy (site A) in *c.* 1887, AD 1920; Bw = Winter bark

Figure 115: Tree-ring series from Achanalt.

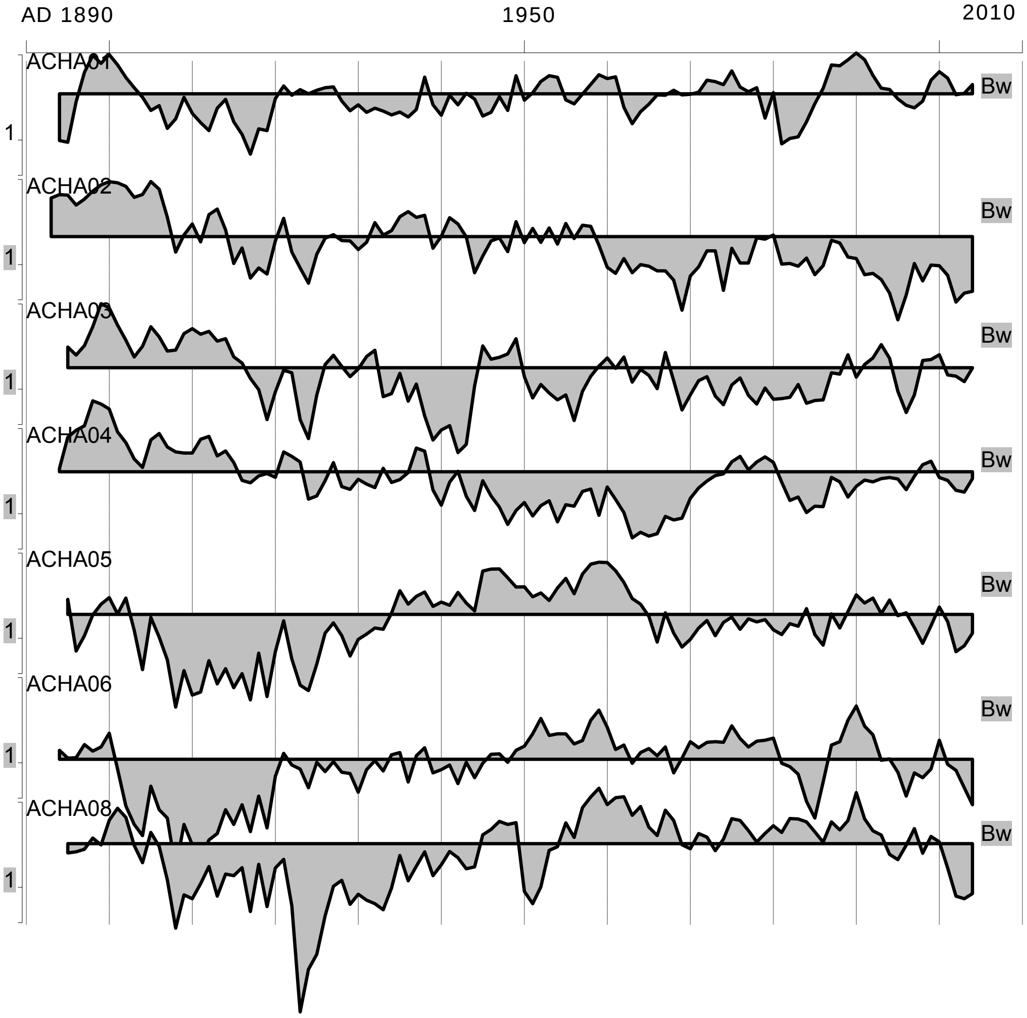
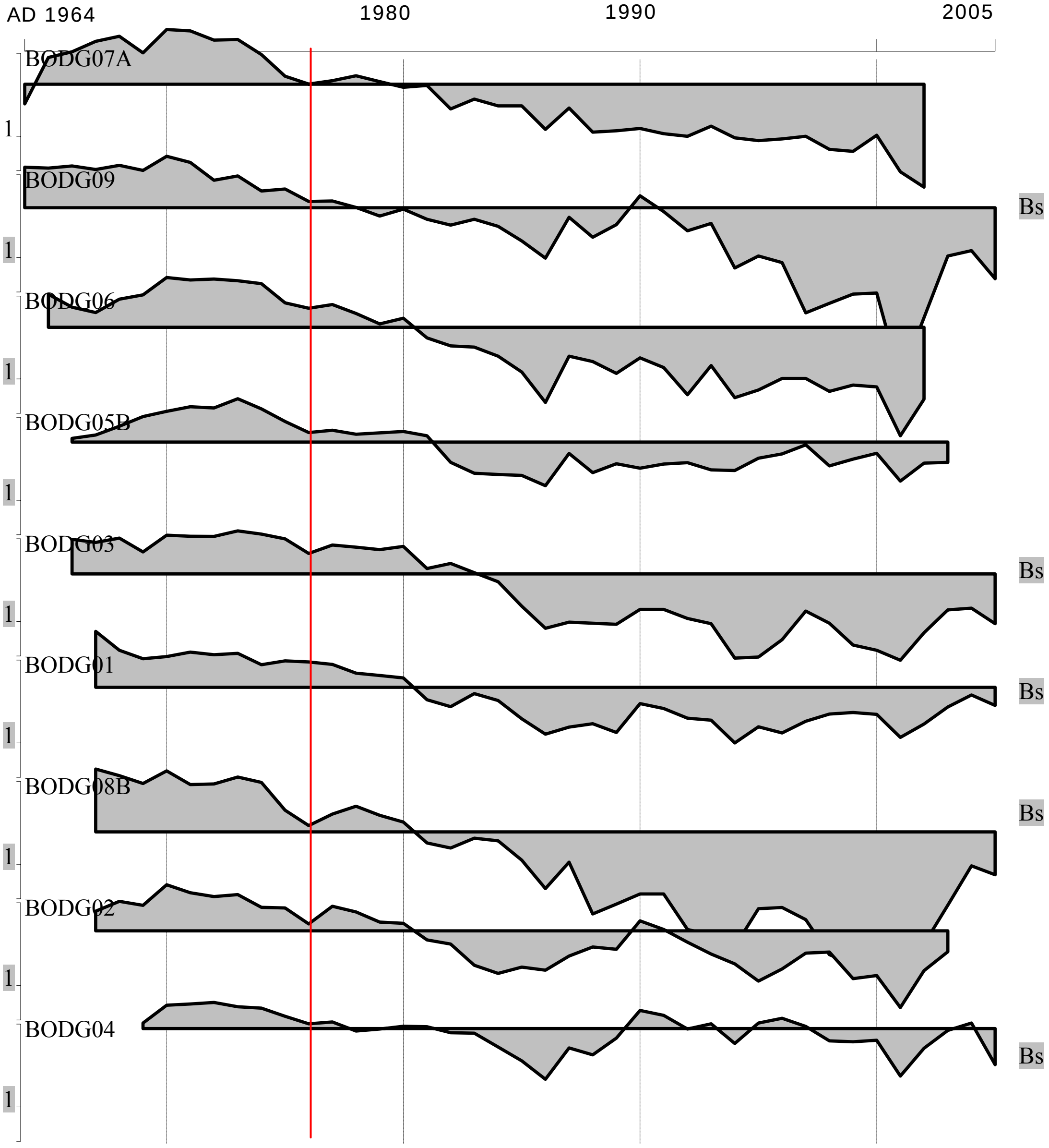
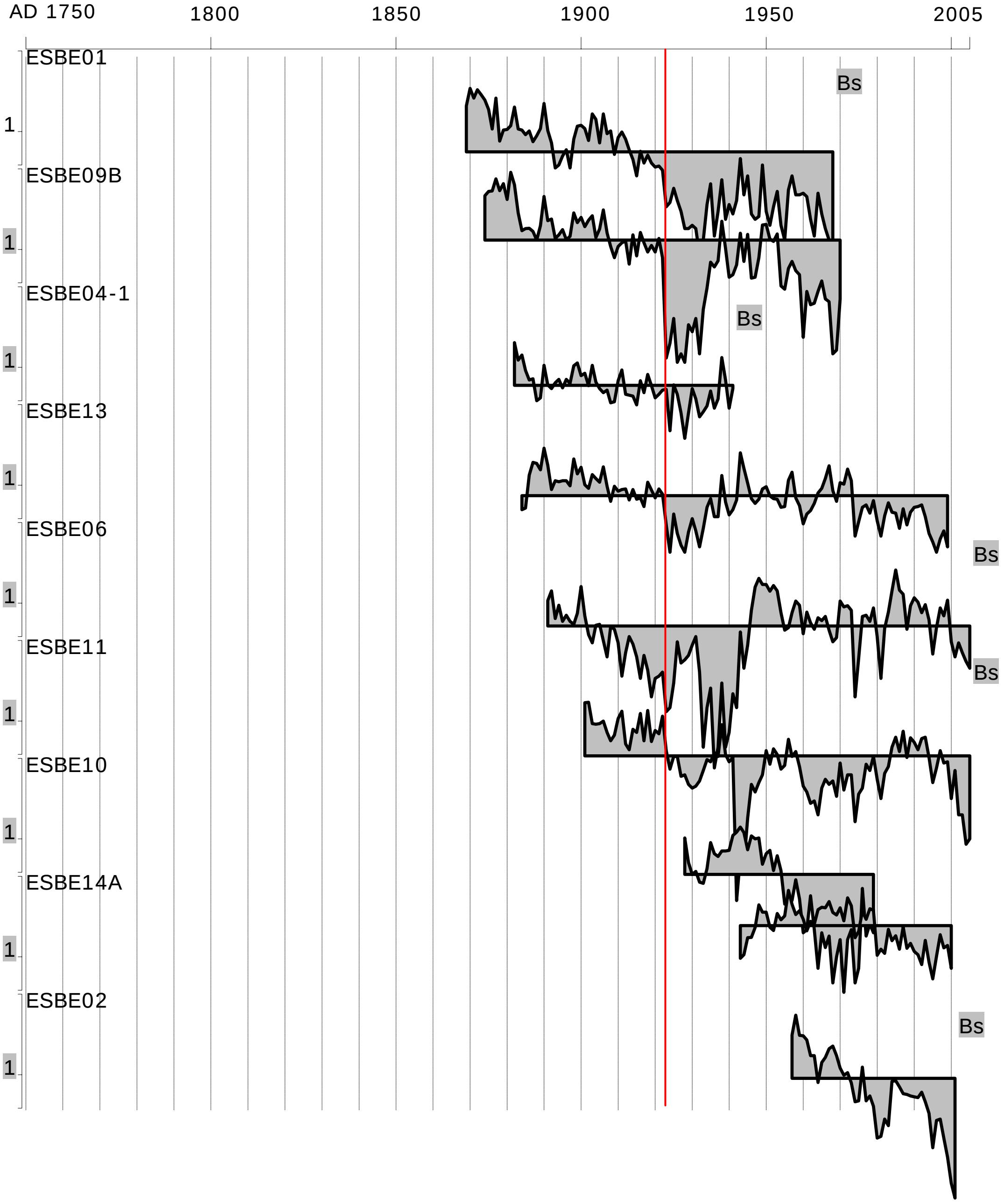


Figure 116: Tree-ring series from Borgie - showing a common growth reduction from the 1980s.



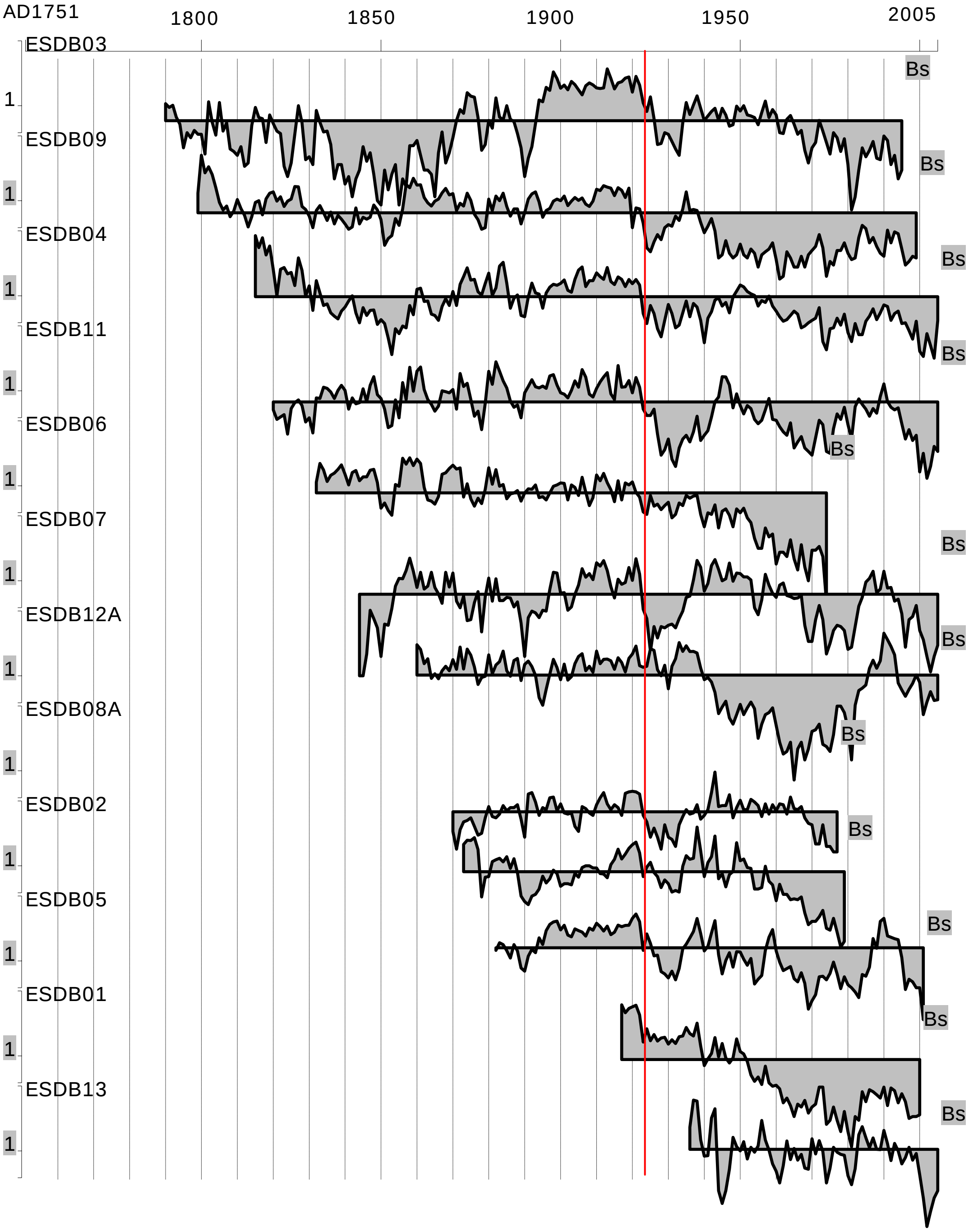
Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of a site wide growth reduction in 1976; Bs = Summer bark.

Figure 117: Tree-ring series from Eilean Sùbhainn (site A) - showing common reduction in growth from the 1923.



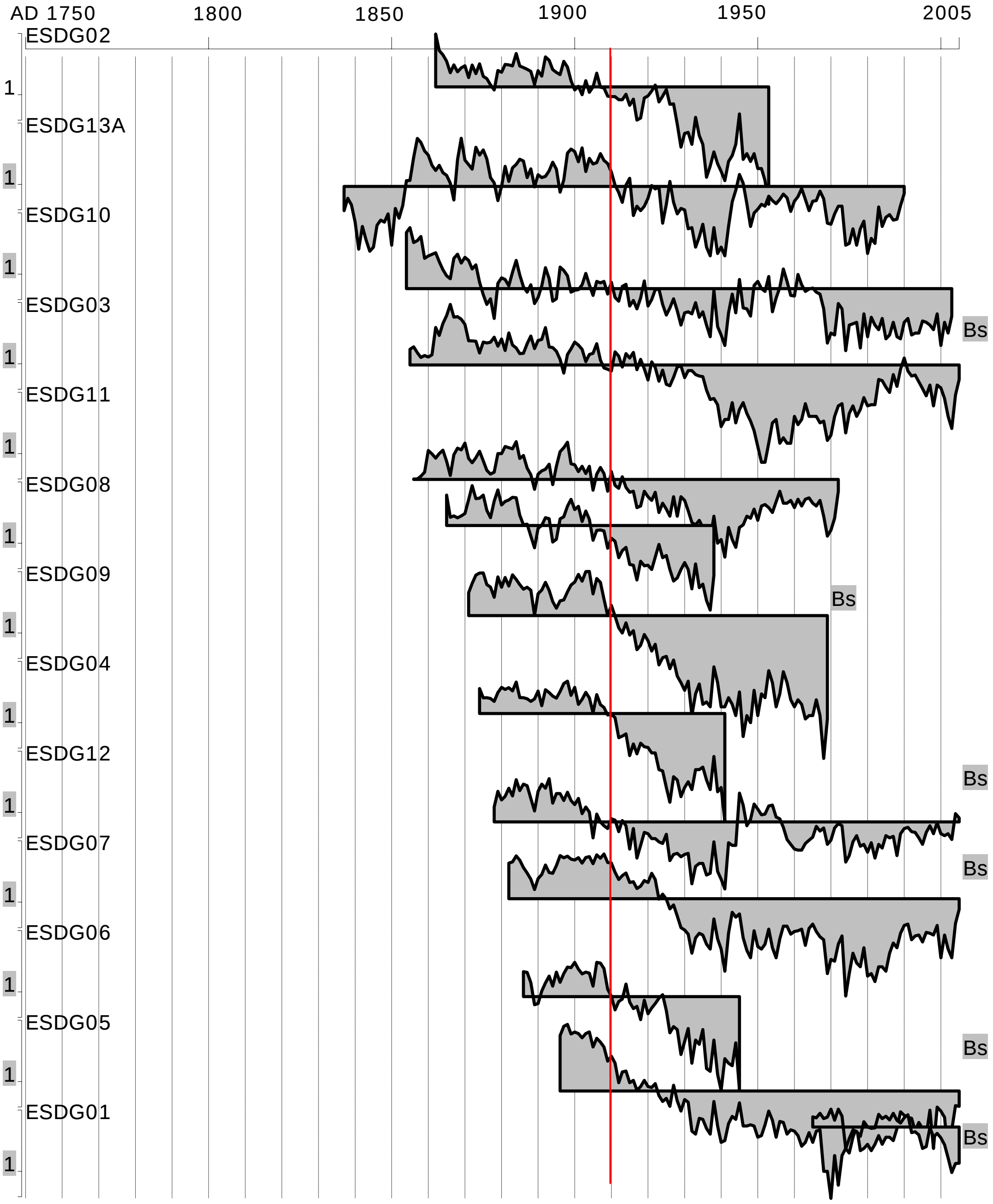
Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of a site wide growth reduction in 1923; Bs = Summer bark.

Figure 118: Tree-ring series from Eilean Sùbhainn (site B) - showing common reduction in growth from the *c.* 1923.



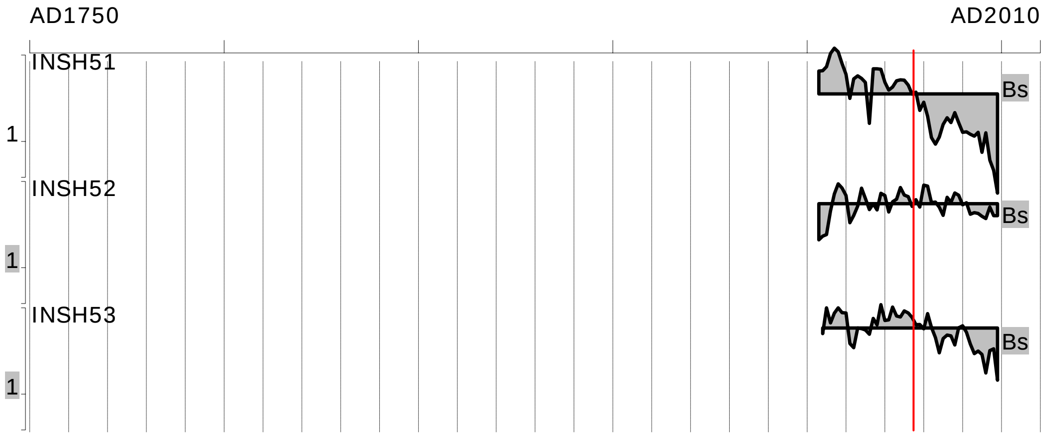
Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of a site wide growth reduction in 1923; Bs = Summer bark.

Figure 119: Tree-ring series from Eilean Sùbhainn (site C) showing common reduction in growth from the *c.* 1910.



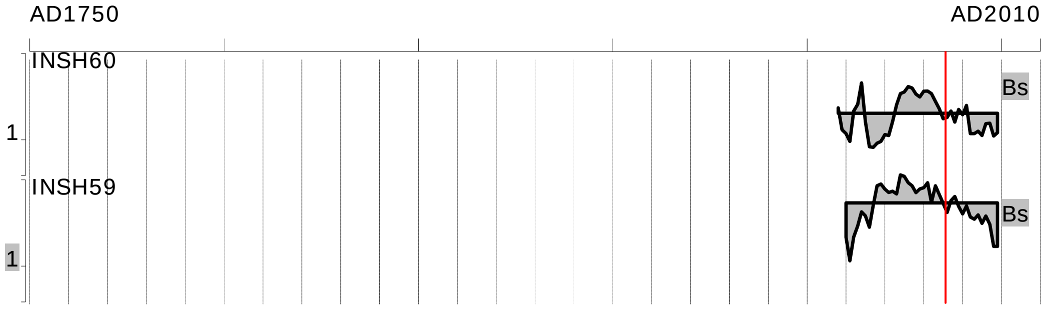
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of a site wide growth reduction in 1910; Bs = Summer bark

Figure 120: Tree-ring series from Inshriach (site A).



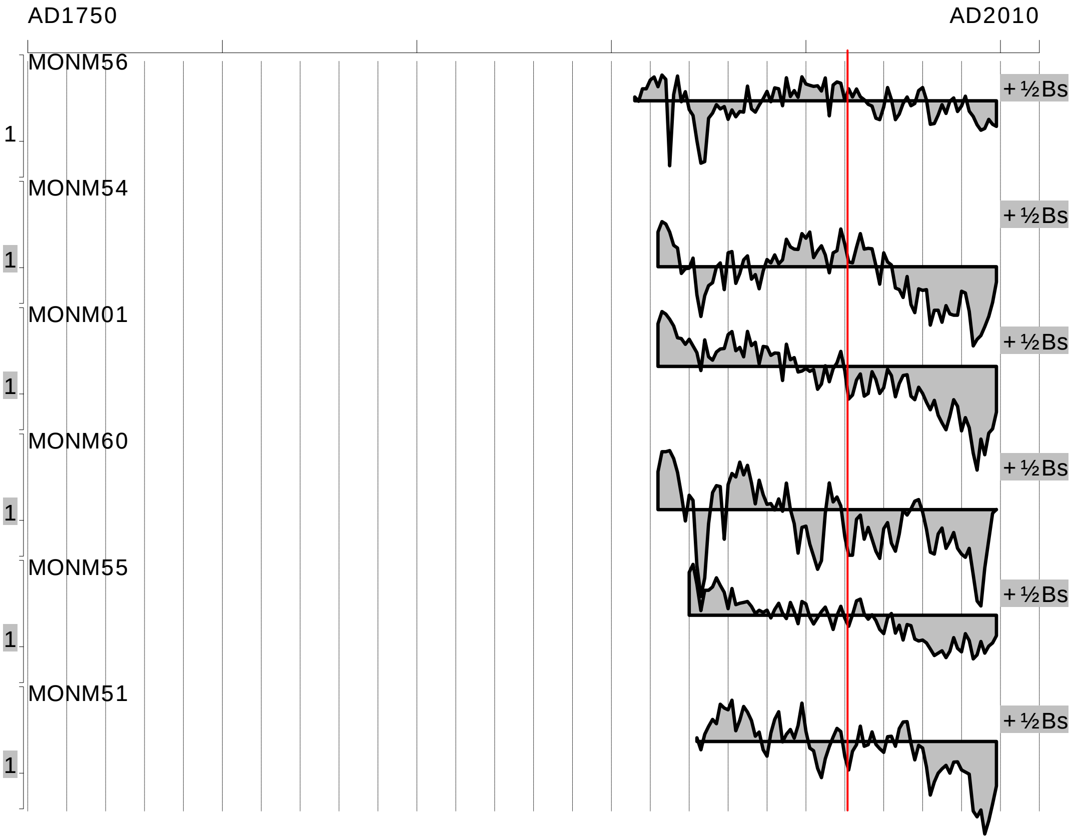
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of growth reduction in 1978; Bs = Summer bark.

Figure 121: Tree-ring series from Inshriach (site B).



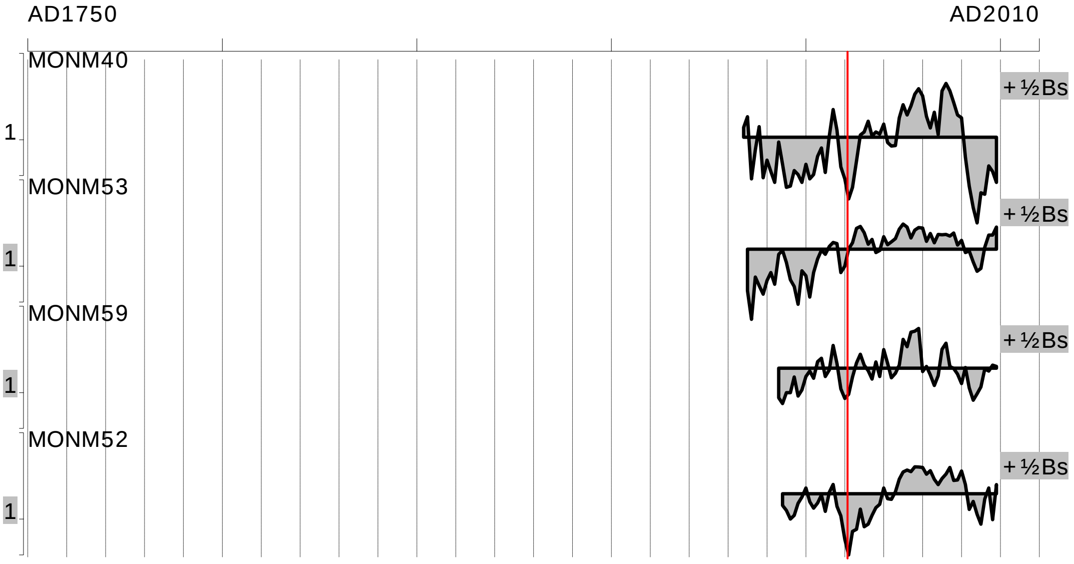
Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of growth reduction in 1986; Bs = Summer bark.

Figure 122: Tree-ring series from Monadh Mor (site A).



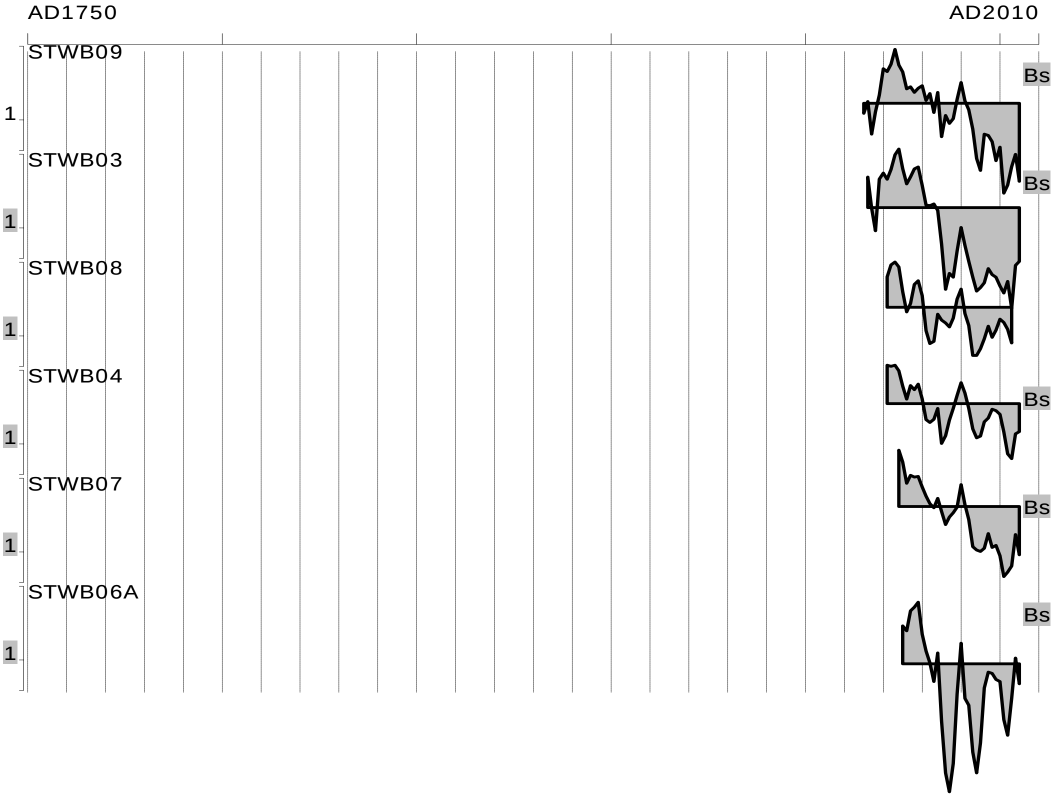
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of a sharp growth reduction from 1961; Bs = Summer bark.

Figure 123: Tree-ring series from Monadh Mor (site B).



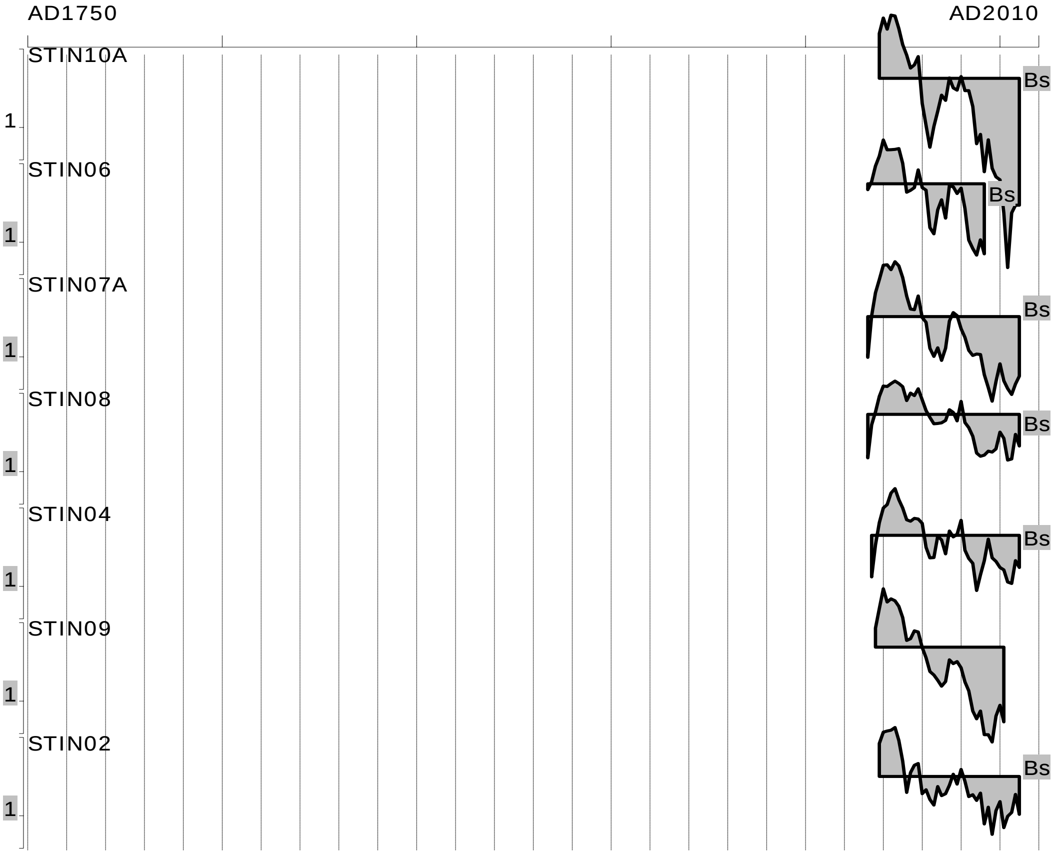
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of a sudden growth reduction from 1961, which lasts less than 10 years before recovery; Bs = Summer bark

Figure 124: Tree-ring series from Strathnaver Forest (site B).



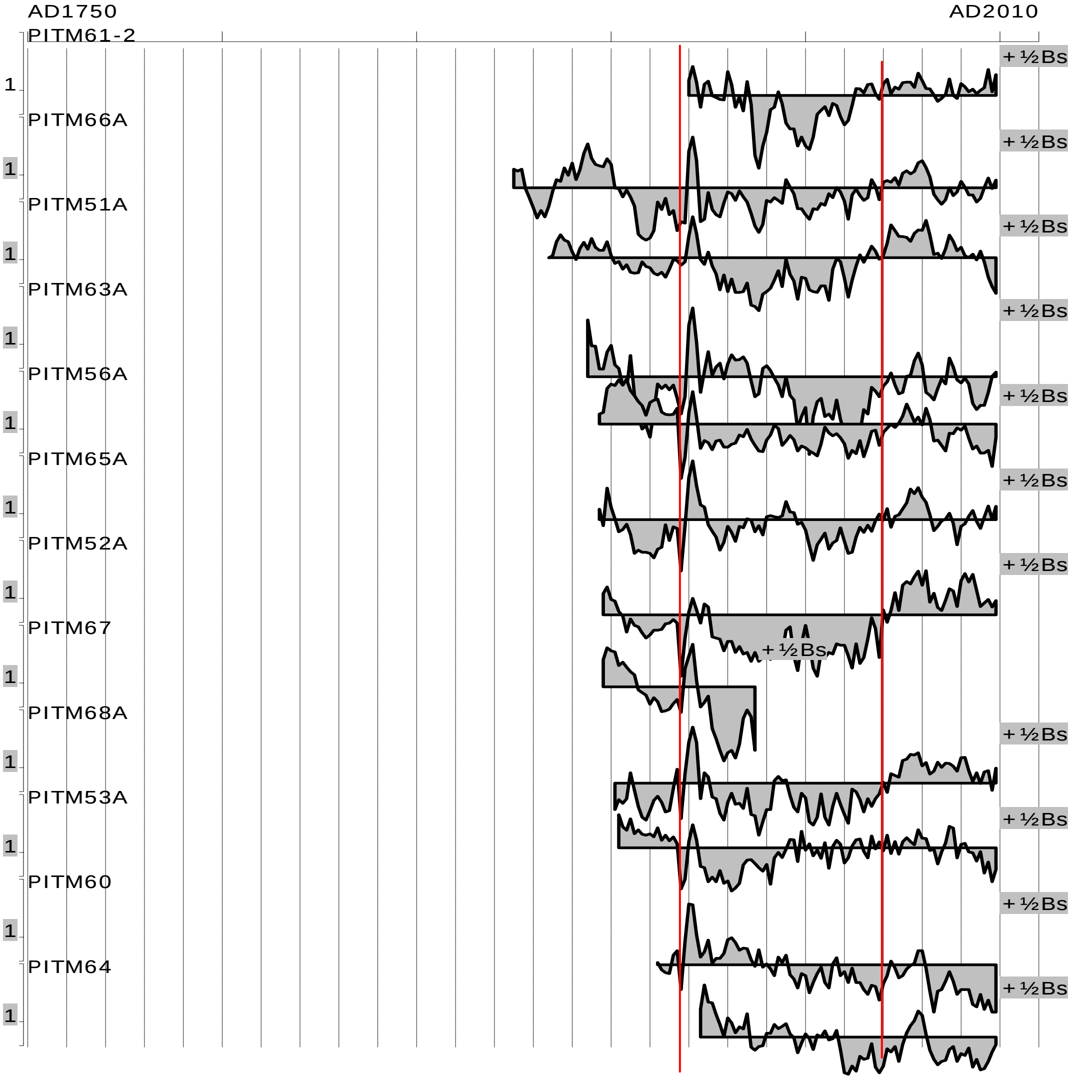
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis; Bs = Summer bark

Figure 125: Tree-ring series from Strathnaver Forest (site C).



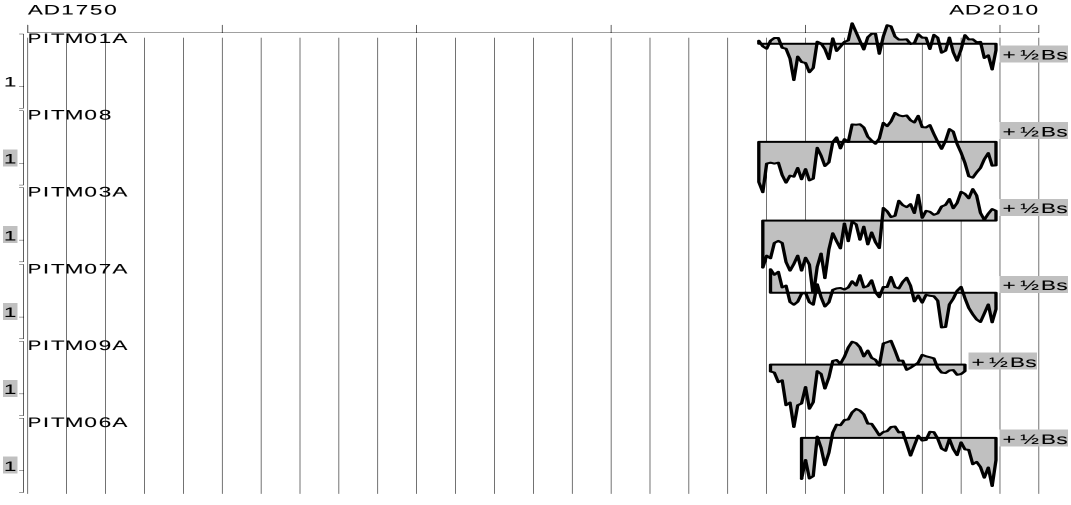
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis; Bs = Summer bark

Figure 126: Tree-ring series from Pitmaduthy (site A).



Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of a sudden growth reduction from 1961, which lasts less than 10 years before recovery +½Bs = Spring bark

Figure 127: Tree-ring series from Pitmaduthy (site B).

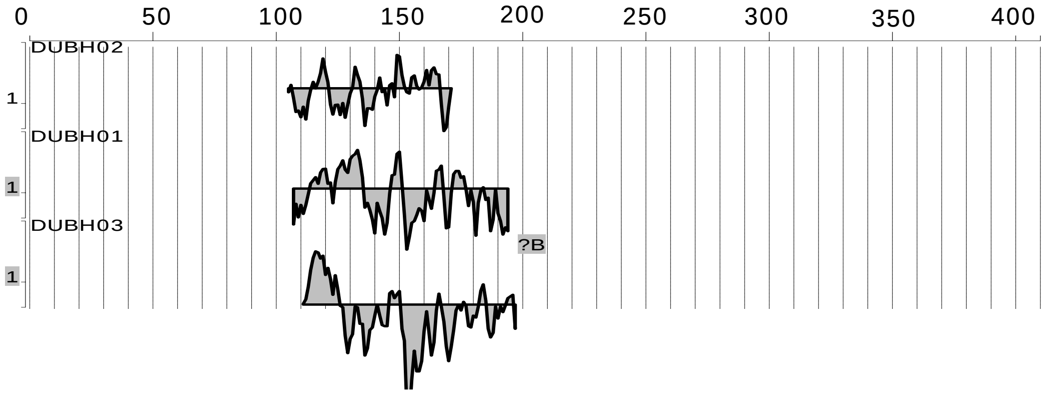


Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis; vertical solid lines indicates the initiation of a sudden growth reduction from 1961, which lasts less than 10 years before recovery +½Bs = Spring bark

7.6 Appendix VI: Plots of Holocene tree-ring series

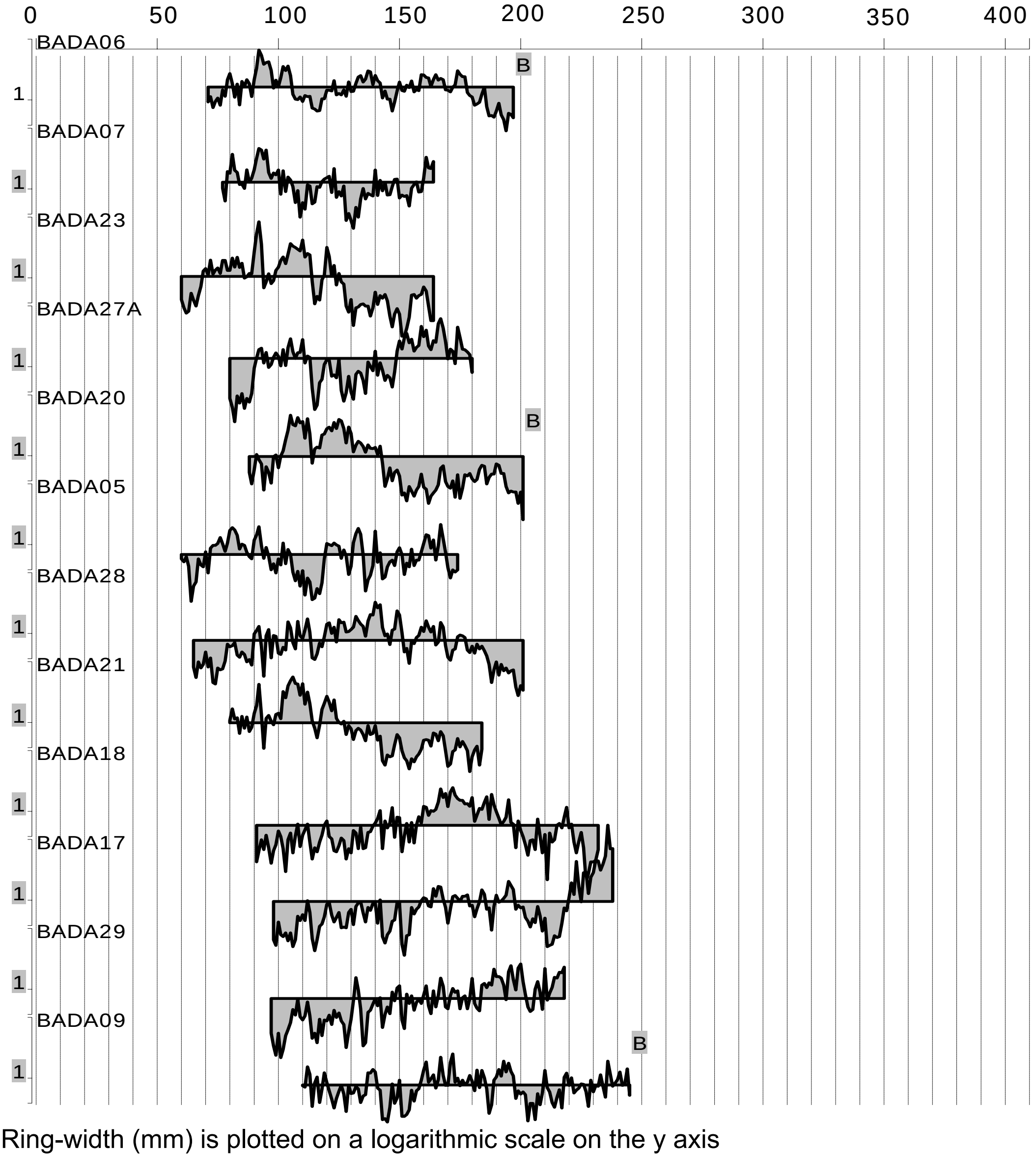
Key: Ring width (mm) is plotted on a logarithmic scale on the y axis; Bs = Summer bark

Figure 128: Tree-ring series from An Dubh-loch.



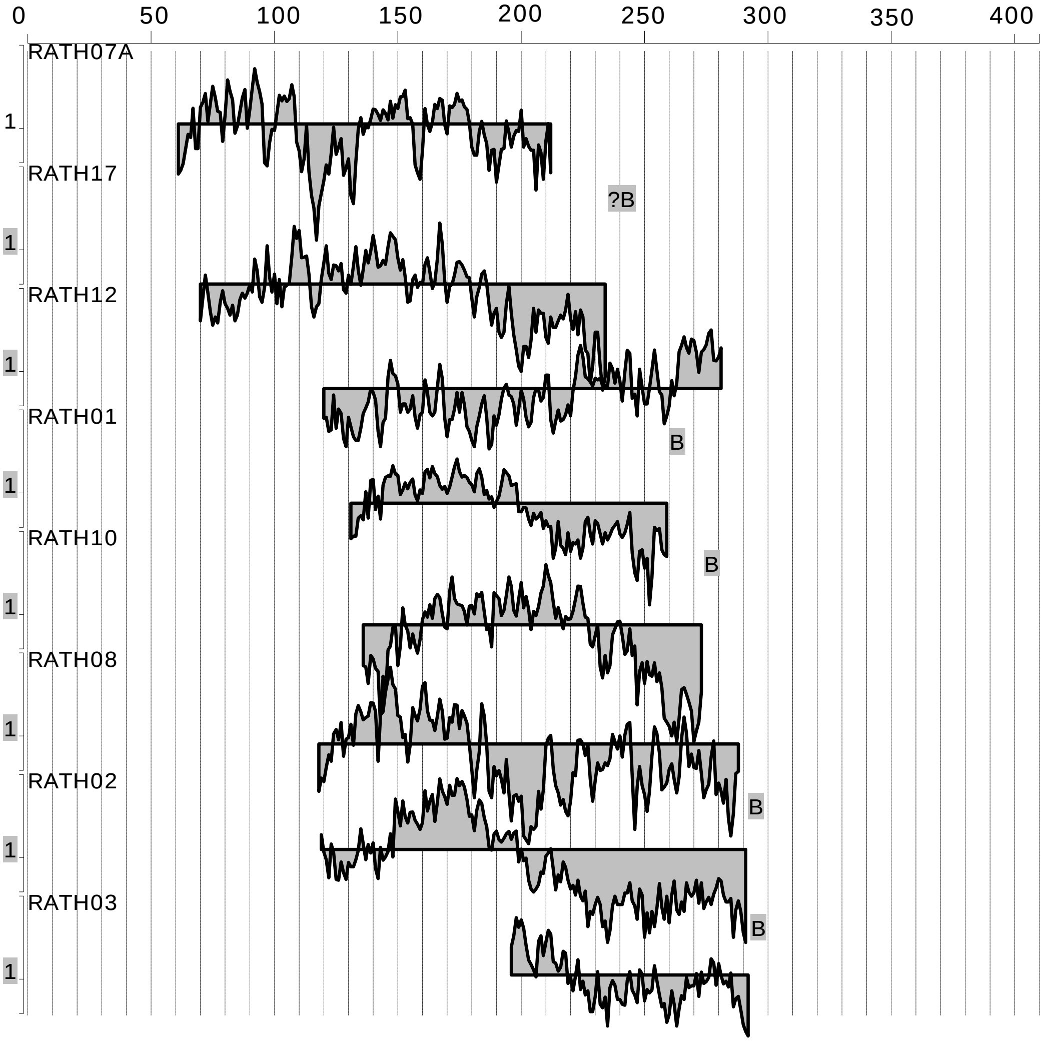
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis

Figure 129: Tree-ring series from Druim Bad a' Ghaill.



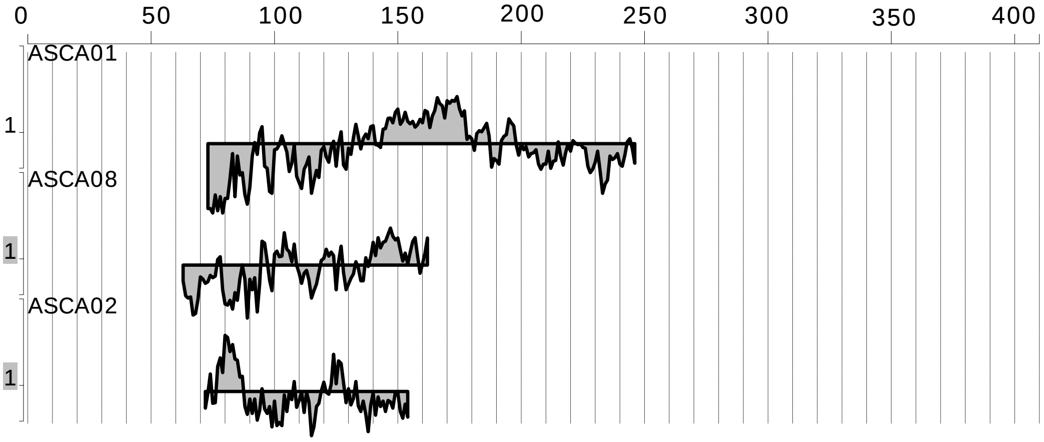
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis

Figure 130: Tree-ring series from Loch an Ruathair.



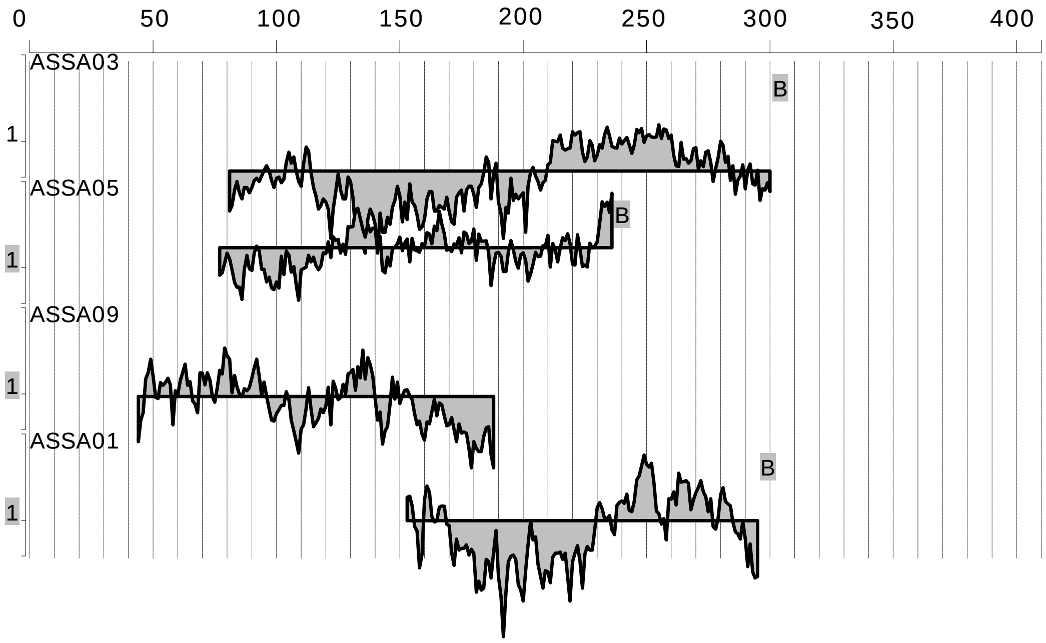
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis

Figure 131: Tree-ring series from Loch Ascaig.



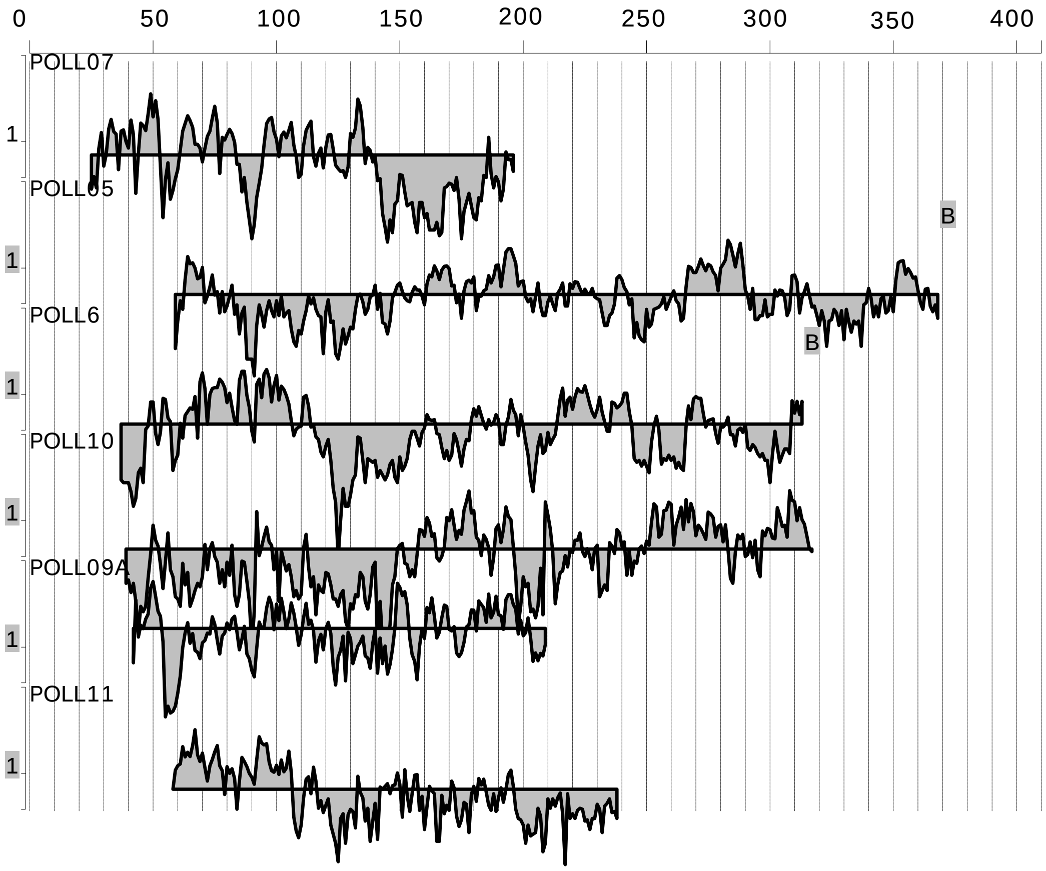
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis

Figure 132: Tree-ring series from Loch Assynt.



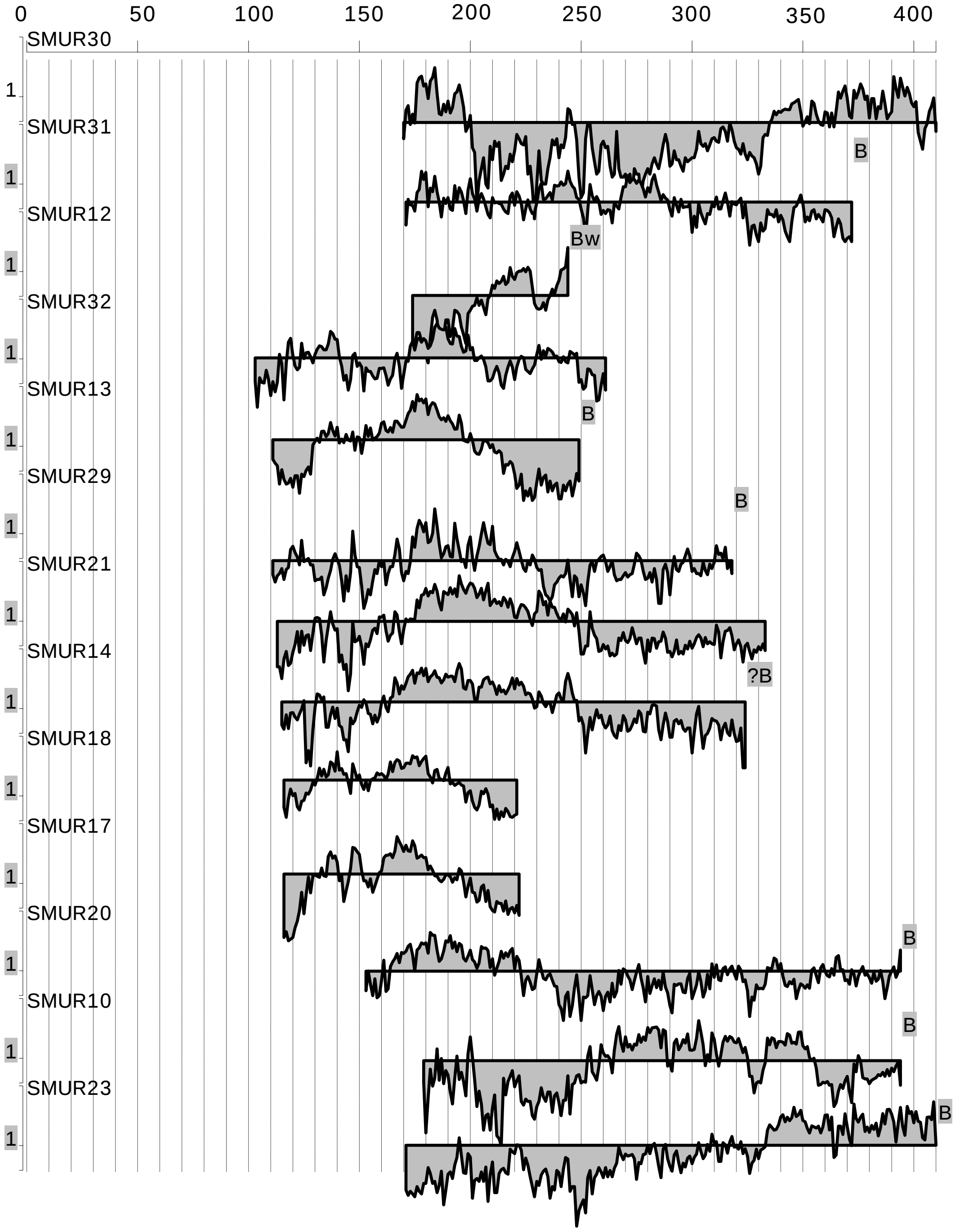
Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis

Figure 133: Tree-ring series from Polla on Loch Eriboll.



Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis

Figure 134: Tree-ring series from Strath Kanaird.



Key: Ring-width (mm) is plotted on a logarithmic scale on the y axis

7.7 Appendix VII: Decadal radial growth rate histograms

Figure 135: Decadal radial growth rates - north coast mineral sites.

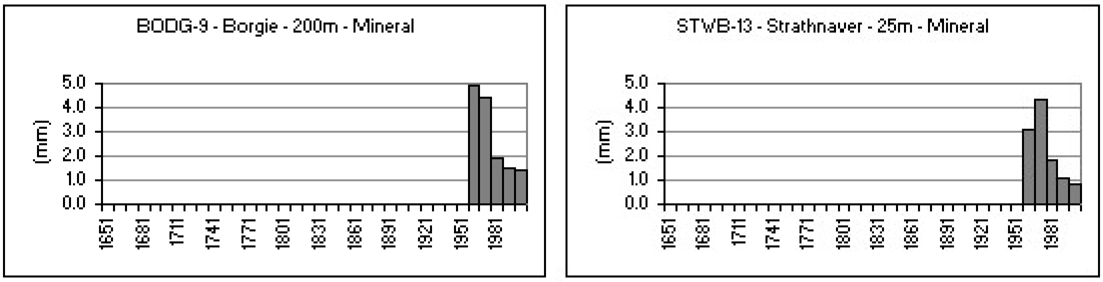


Figure 136: Decadal radial growth rates - NW Highlands - mineral sites – 12m to 300m altitude.

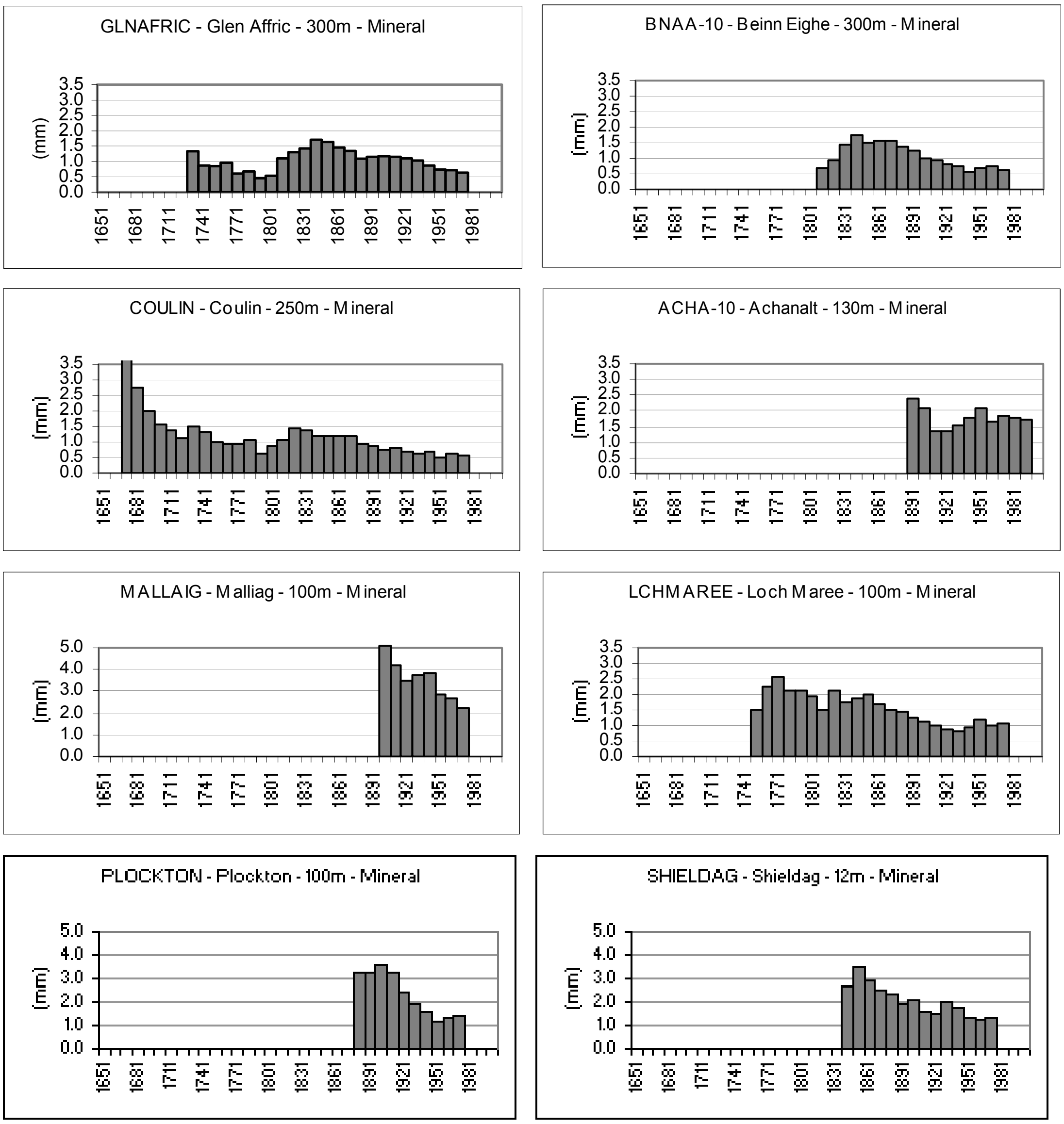


Figure 137: Decadal radial growth - NW Highlands peat and mineral substrate sites

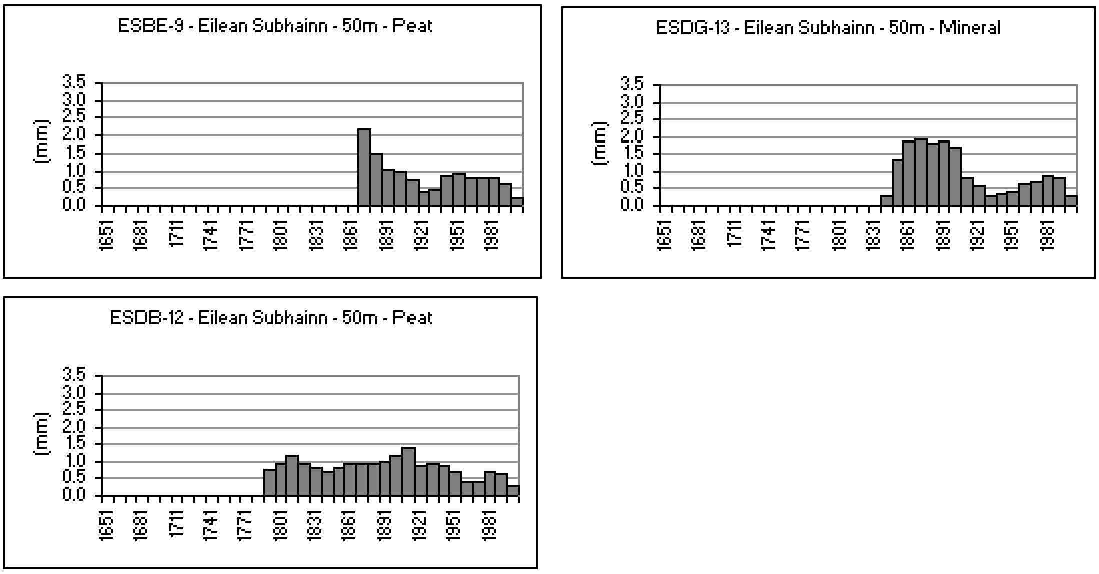


Figure 138: Decadal radial growth rates - Caringorms - mineral sites - over 380m altitude.

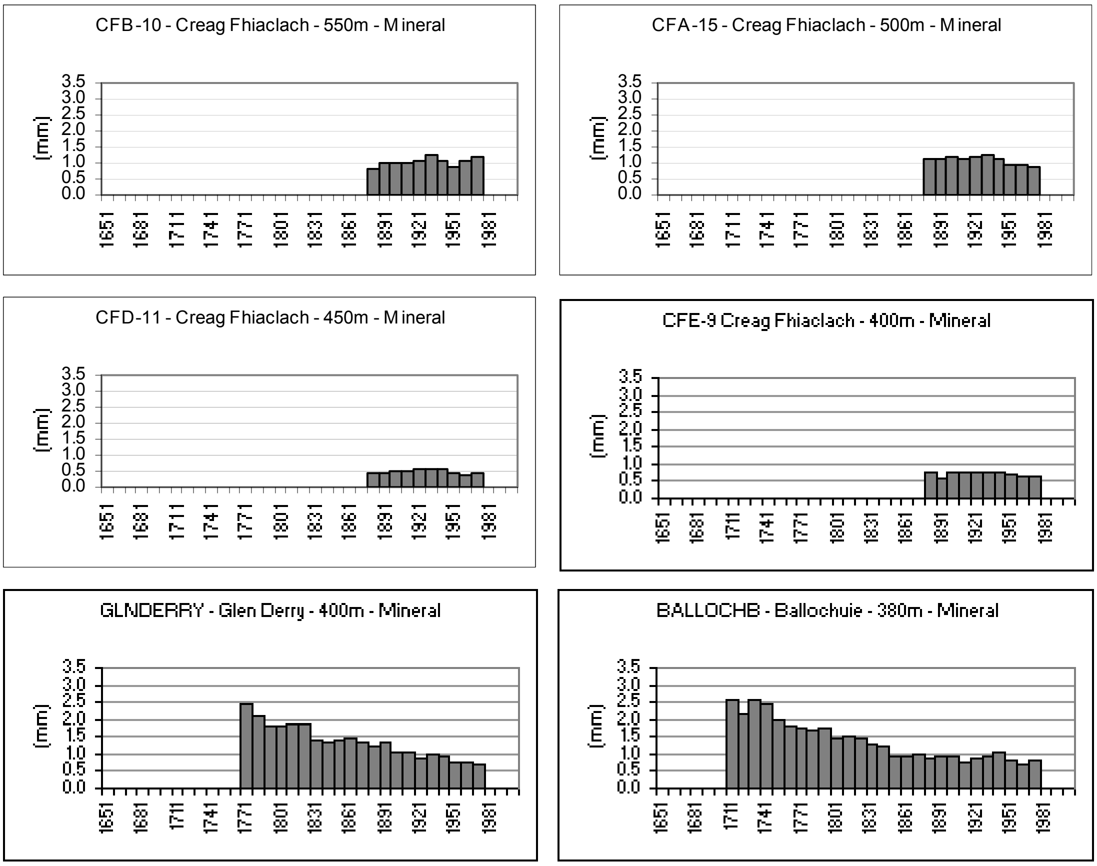


Figure 139: Decadal radial growth rates - Cairngorms - mineral sites – 100m to 300m altitude.

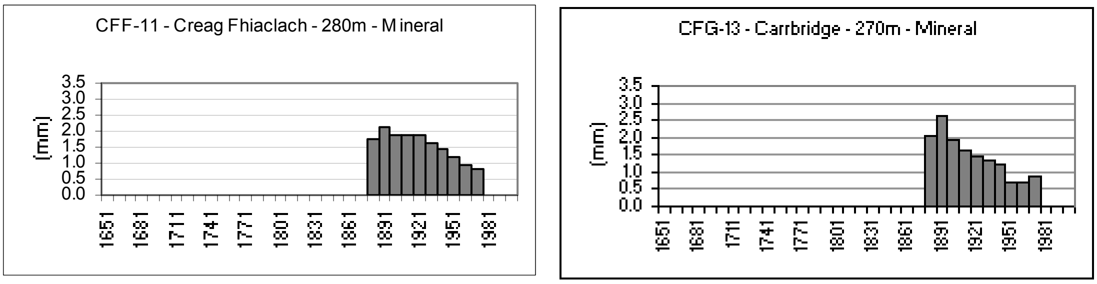


Figure 140: Decadal radial growth rates - mineral site – 200m altitude.

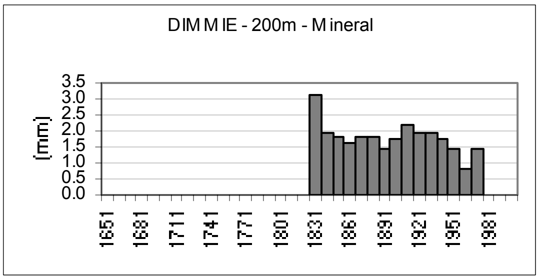


Figure 141: Decadal radial growth rates - peat and mineral sites – 100m to 300m altitude.

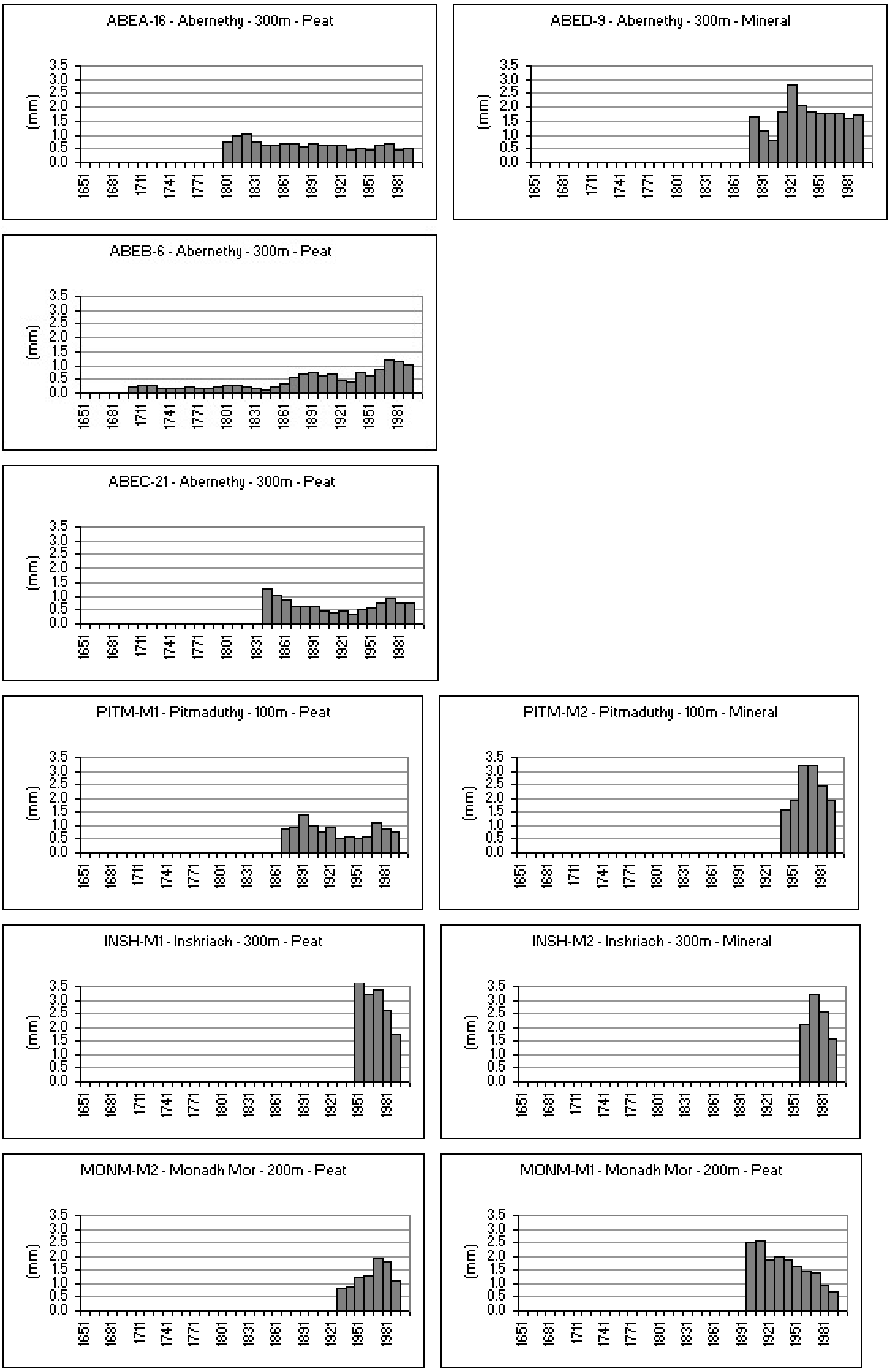
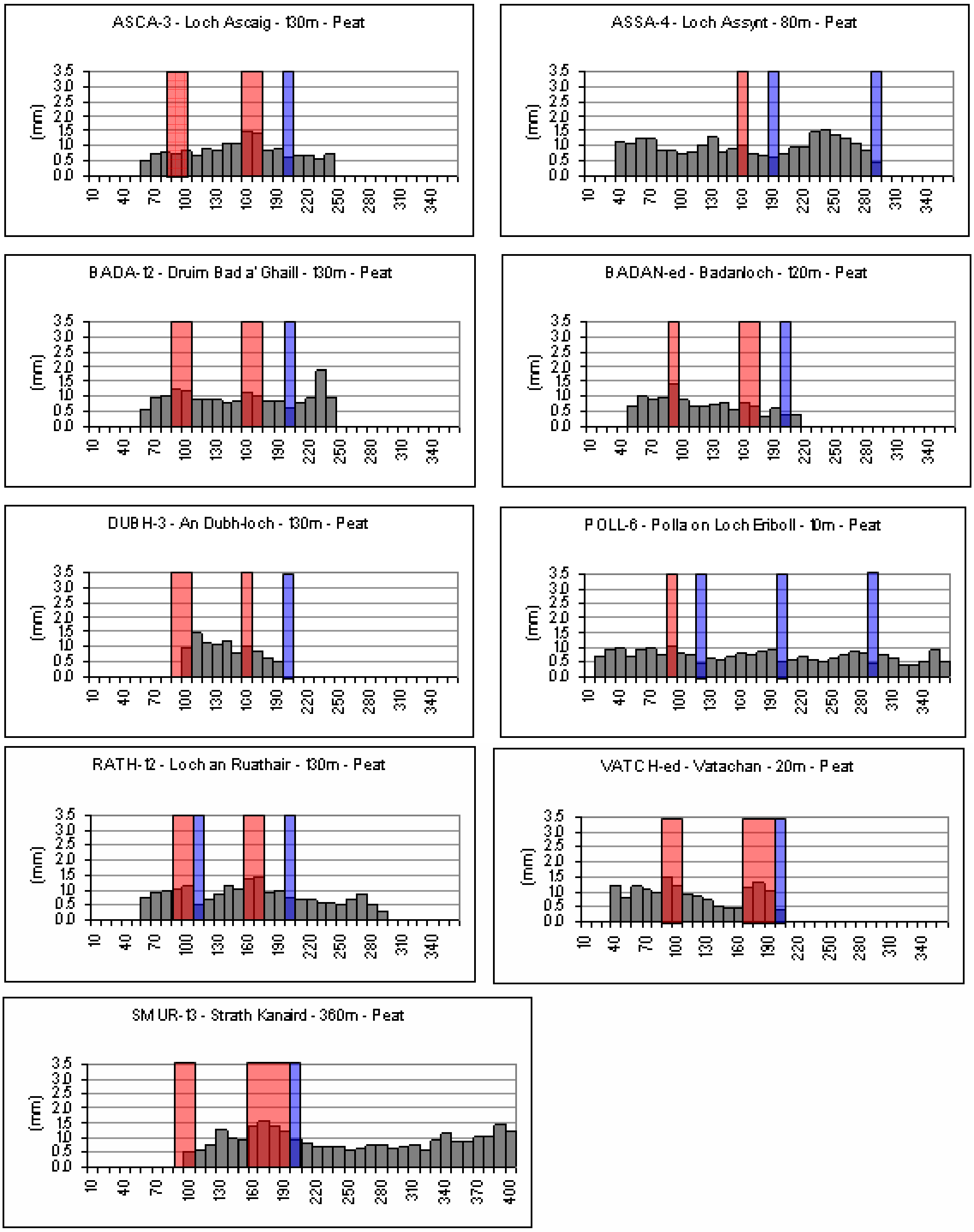


Figure 142: Decadal radial growth rates – Neolithic pine sites.



Key: Red = common periods of high growth & germination. Blue = common periods of low growth or return to lower growth & high mortality.

7.8 Appendix VIII: Age trend decadal radial growth rate histograms

Figure 143: Age trend radial growth rates - North coast mineral sites.

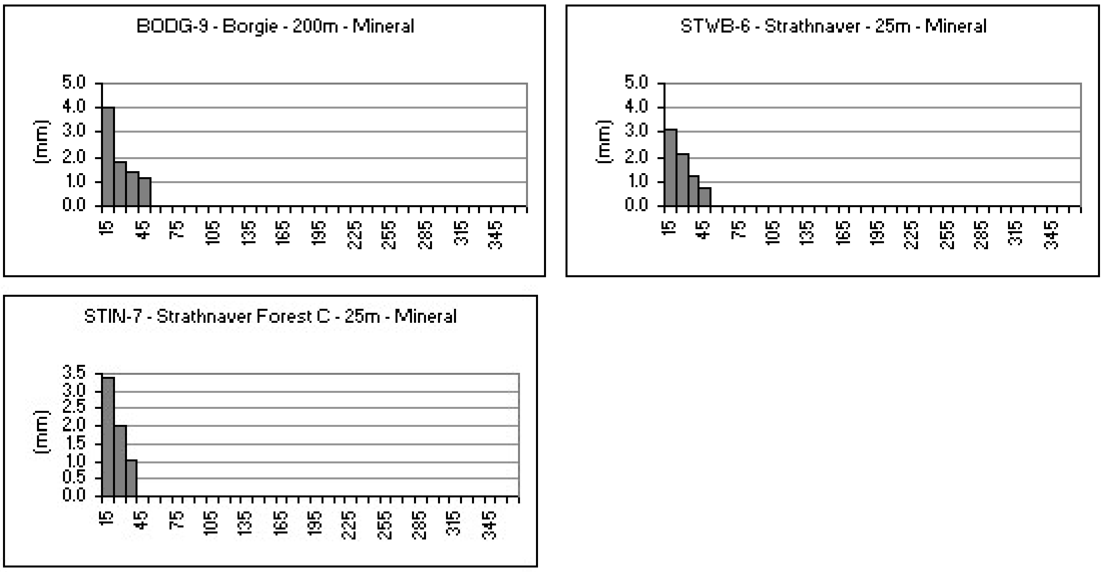


Figure 144: Age trend radial growth rates - NW Highlands - mineral sites – 12m to 300m altitude.

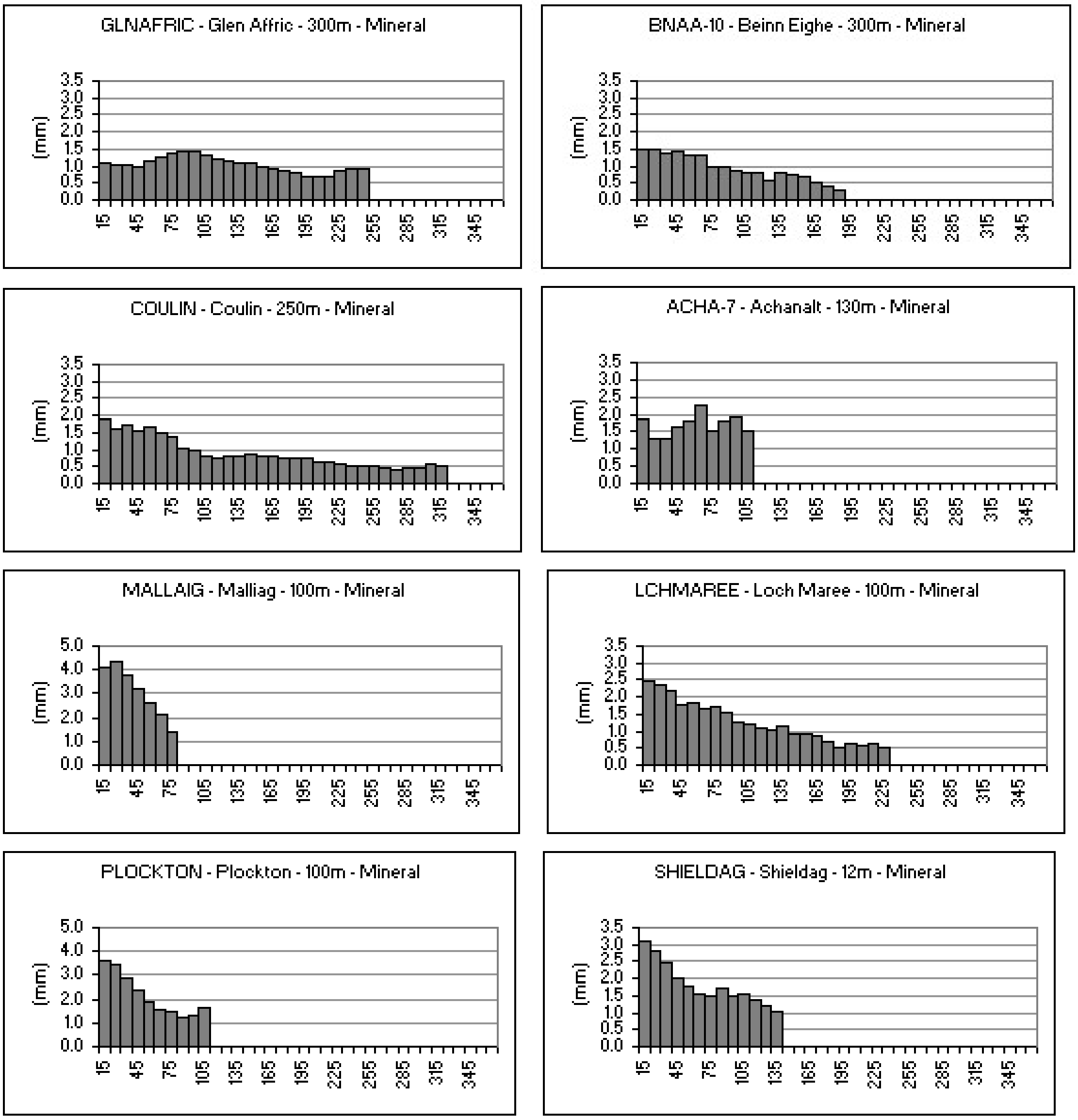


Figure 145: Age trend radial growth rates - NW Highlands peat and mineral substrate sites.

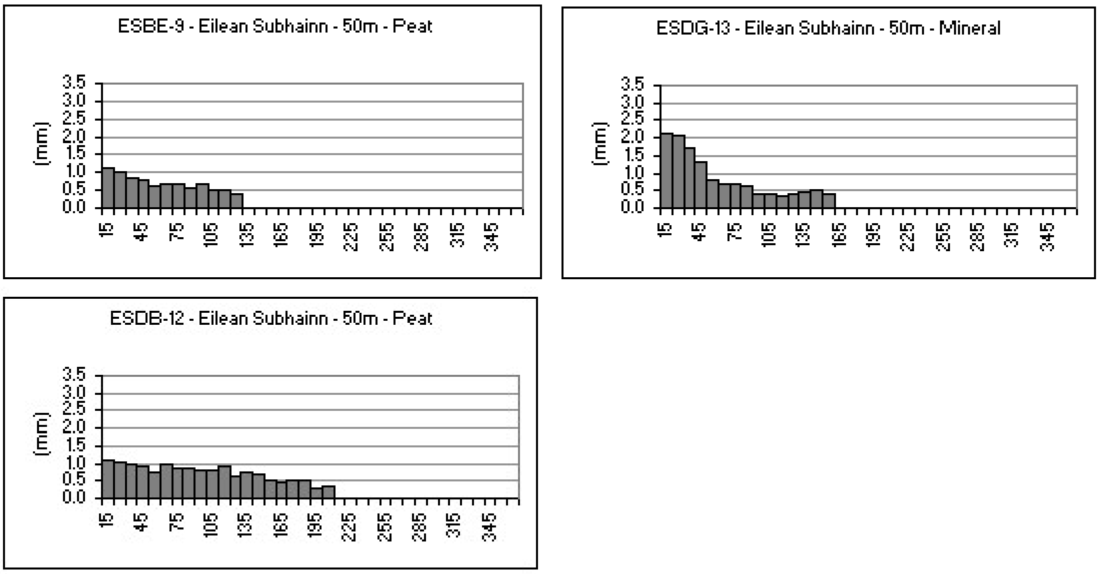
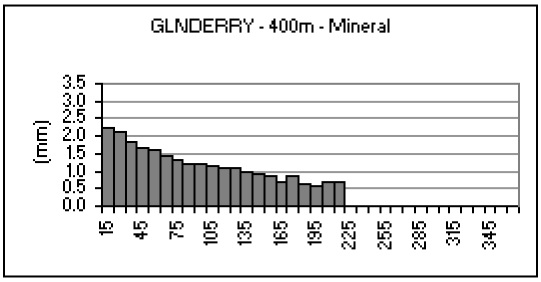


Figure 146: Age trend radial growth rates - Caringorms - mineral sites - over 380m altitude.



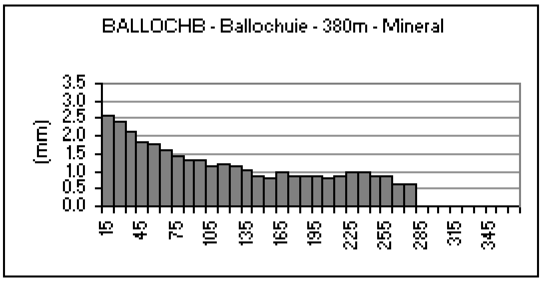


Figure 147: Age trend radial growth - mineral sites - 200m altitude.

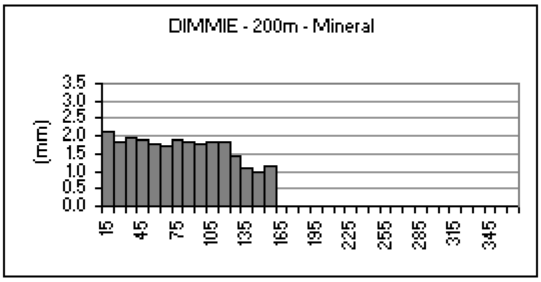


Figure 148: Age trend radial growth rates - peat and mineral sites – 100m to 300m altitude.

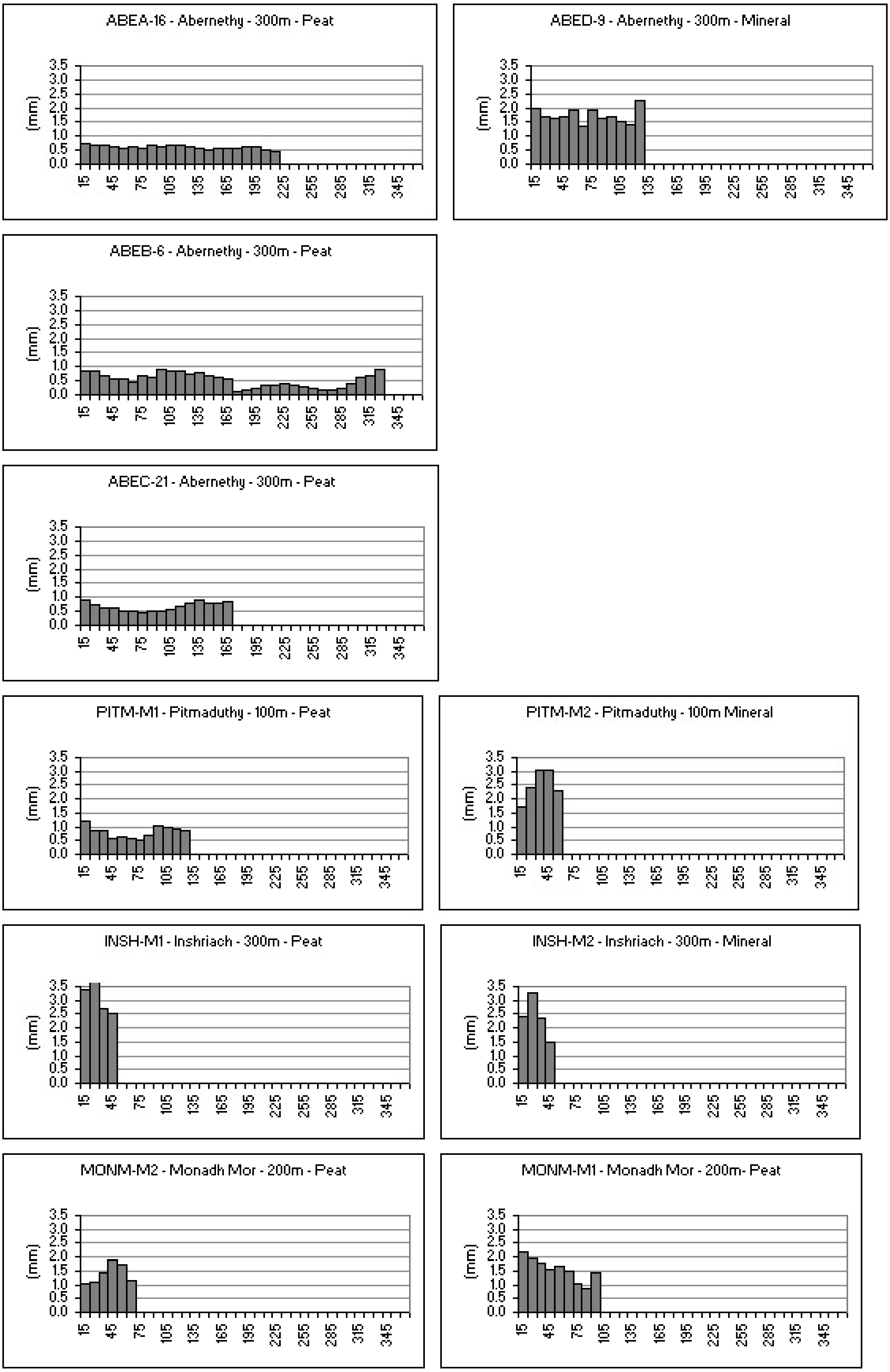
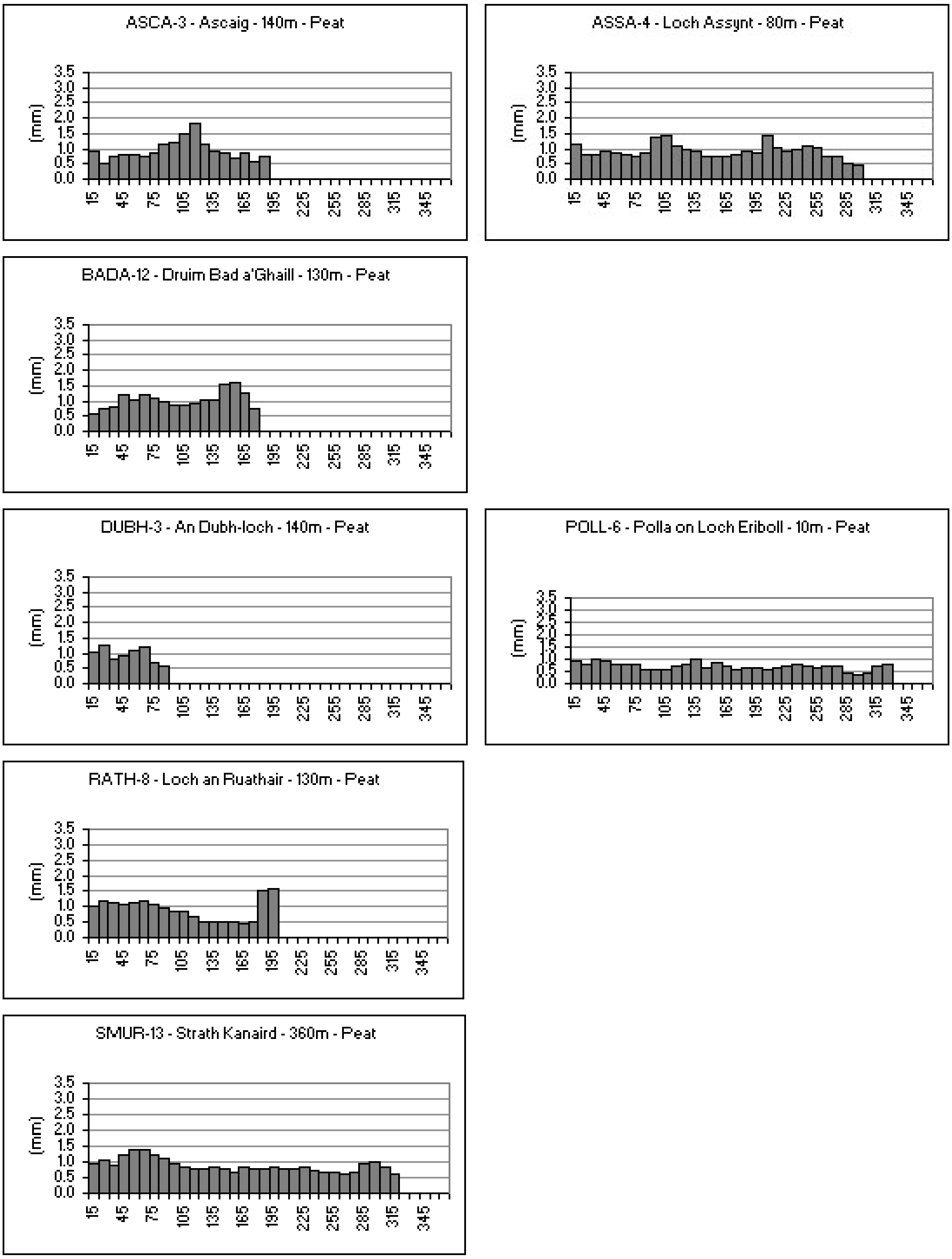


Figure 149: Age trend radial growth rates – Neolithic pine sites.



7.9 Appendix IX: Raw tree-ring data

Table 60: Boreal pine data - Scotland [BORAL-PN] 11 chronology mean.
Ring-width PISY data of 295 years length
Dated AD1706 to 2000, Average ring width 146.53, Sensitivity 0.11

AD1706						169	205	195	230	179
	113	253	213	195	229	257	218	244	232	233
	221	217	213	222	209	215	249	254	264	247
	207	209	211	277	273	243	205	269	226	204
	237	224	228	223	210	196	226	206	205	236
AD1751	192	216	199	240	220	186	166	136	166	163
	180	146	176	186	164	210	199	211	209	166
	127	139	178	181	201	238	197	195	236	206
	201	172	209	175	154	146	174	162	183	179
	191	179	142	160	159	158	148	148	128	148
AD1801	141	143	156	154	151	138	138	145	135	123
	144	157	171	144	147	132	159	149	187	157
	147	164	152	171	161	142	171	164	154	168
	181	174	150	167	141	109	113	109	103	111
	117	108	125	107	110	137	137	135	129	126
AD1851	122	125	102	125	103	99	120	108	113	103
	115	133	146	127	109	101	88	113	89	99
	102	106	97	119	130	106	91	114	89	120
	86	125	97	114	102	100	108	101	96	128
	123	124	127	111	86	103	117	119	115	108
AD1901	112	94	108	120	113	103	100	96	100	107
	104	110	114	121	103	114	109	119	114	93
	103	101	115	128	139	154	132	108	124	119
	122	128	121	114	133	114	107	118	116	88
	95	94	119	117	107	97	93	86	117	96
AD1951	88	90	94	87	82	74	80	82	85	74
	57	79	84	97	90	88	98	87	86	94
	120	115	98	85	98	77	75	91	103	183
	196	157	160	164	160	156	178	150	144	164
	162	147	168	188	173	176	195	156	164	174

Table 61: Oceanic pine data- Scotland [OCEAN-PN] 7 chronology mean.
Ring-width PISY data of 335 years length
Dated AD1671 to 2005, Average ring width 153.58, Sensitivity 0.12

AD1671	386	414	339	382	248	261	255	426	603	476
	351	300	210	247	285	275	268	237	229	325
	289	232	226	209	196	163	187	162	156	171
AD1701	171	102	124	133	161	182	181	168	177	182
	186	209	161	134	138	129	90	85	111	122
	100	99	92	107	107	124	123	132	106	112
	113	135	148	208	214	167	135	129	117	104
	113	118	147	143	148	147	165	136	112	113
AD1751	115	124	125	94	91	101	123	82	158	136
	113	124	152	116	180	177	201	221	156	151
	128	141	151	174	191	183	158	159	224	228
	178	146	167	127	157	146	164	171	181	145
	172	135	137	133	147	133	123	143	116	129
AD1801	121	111	144	175	168	136	140	154	117	122
	118	112	103	99	100	89	113	123	129	112
	144	156	150	153	146	147	151	159	151	150
	145	159	169	187	177	140	106	116	119	116
	102	114	130	103	123	145	177	195	186	155
AD1851	181	184	157	203	183	208	207	215	191	178
	186	193	180	176	192	170	164	202	188	192
	170	190	183	204	194	172	149	143	177	239
	199	213	201	229	192	163	181	167	141	183
	162	187	209	162	156	171	187	222	212	210
AD1901	199	183	181	191	186	193	151	156	157	170
	163	169	176	164	137	129	102	110	114	119
	155	135	109	99	113	121	122	103	105	112
	113	114	121	112	130	112	114	130	94	87
	96	94	109	102	124	105	118	110	132	112
AD1951	108	109	114	94	103	89	109	116	116	102
	102	106	101	114	107	101	117	107	86	94
	101	116	113	91	117	120	97	94	103	97
	77	82	94	90	85	84	121	104	123	197
	173	144	133	123	98	96	122	109	138	135
AD2001	111	82	77	103	82					

Table 62: Boreal bog pine data - Scotland [BORAL-BP] 3 chronology mean
Ring-width PISY data of 307 years length
Dated AD1694 to 2000, Average ring width 48.35, Sensitivity 0.20

AD1694				29	19	20	23	23	21	33
AD1701	27	29	31	20	21	24	19	18	21	24
	39	40	26	22	39	17	15	24	35	27
	33	21	23	18	32	29	28	27	30	19
	15	19	15	21	22	23	28	27	14	10
	13	19	25	25	26	21	20	12	10	20
AD1751	13	11	17	18	13	9	11	16	23	20
	26	21	15	24	31	25	22	15	16	8
	9	9	10	16	35	17	12	18	11	19
	18	22	18	16	23	16	12	20	25	16
	18	18	15	24	23	19	20	48	36	21
AD1801	21	25	33	56	51	69	78	80	55	46
	77	79	63	57	50	42	50	59	68	73
	49	58	50	50	49	71	75	92	78	53
	47	59	50	56	52	44	54	60	62	48
	50	44	66	70	85	86	92	68	52	61
AD1851	63	64	77	70	74	77	48	59	48	58
	72	70	47	31	35	54	66	84	69	82
	60	77	71	63	63	64	80	62	51	44
	42	59	53	56	67	60	57	69	77	94
	72	84	86	76	58	48	64	57	56	71
AD1901	67	57	61	62	46	46	55	56	58	66
	56	33	45	60	57	77	77	58	57	32
	38	47	64	80	70	41	50	50	37	29
	33	26	32	34	53	41	34	41	59	50
	45	40	52	51	66	61	68	63	81	56
AD1951	59	51	50	51	53	53	69	67	64	57
	59	83	87	99	78	73	71	58	55	73
	103	90	69	73	109	94	97	104	111	101
	104	75	71	77	69	72	87	77	68	77
	82	70	60	65	63	76	90	80	96	85

Table 63: Oceanic bog pine data - Scotland [OCEAN-BP] 2 chronology mean
Ring-width PISY data of 216 years length
Dated AD1790 to 2005, Average ring width 87.63, Sensitivity 0.19

AD1790										105
	96	101	76	64	36	52	46	55	85	176
AD1801	114	169	128	93	102	67	77	51	55	66
	60	46	39	65	207	165	183	138	178	110
	75	101	91	80	92	98	142	102	63	69
	45	101	103	92	83	81	70	80	87	76
	64	77	77	54	69	61	79	85	61	47
AD1851	45	36	38	67	60	94	97	133	110	136
	137	90	85	75	69	71	93	105	130	168
	135	169	152	179	168	152	186	126	153	150
	183	173	128	114	98	95	102	95	84	126
	101	100	86	89	85	93	98	131	122	120
AD1901	114	98	109	108	105	127	99	96	92	113
	110	107	105	99	84	114	105	112	114	106
	123	104	58	55	67	60	46	46	50	50
	50	43	52	64	84	74	87	124	77	55
	66	77	114	70	77	74	79	89	103	99
AD1951	87	82	88	65	59	85	96	94	84	65
	63	59	60	62	64	64	70	55	53	67
	62	84	71	36	44	69	61	62	68	43
	35	50	68	82	90	78	97	70	88	106
	89	80	84	65	45	49	63	54	59	40
AD2001	27	29	28	25	28					

Table 64: Sub-fossil pine data - Northern Scotland [WRATH-9ED] 9 chronology mean
Ring-width PISY data of 230 years length
Tentatively dated 3139 to 2910BC, Average ring width 86.89   Sensitivity 0.12

3139BC		99	120	109	96	88	80	83	62	77
	91	89	102	98	102	102	99	92	91	94
	108	114	102	103	82	87	82	93	81	67
	88	107	174	130	96	116	99	100	93	89
3100BC	92	106	112	89	105	114	100	87	93	71
	76	75	89	91	69	66	66	68	77	97
	100	99	77	77	88	82	83	92	65	75
	87	85	98	109	99	88	72	93	85	91
	106	75	85	63	67	64	81	103	95	124
3050BC	91	123	87	87	69	82	80	75	71	76
	85	114	97	88	102	100	121	133	113	91
	91	104	111	108	124	102	118	113	93	90
	95	74	90	94	110	105	93	69	69	87
	76	71	70	88	94	110	105	89	73	75
3000BC	66	79	69	60	59	65	64	69	64	63
	79	68	71	63	62	72	69	65	84	81
	72	84	85	94	78	75	77	73	60	67
	76	93	88	87	91	92	145	98	102	84
	80	81	81	83	94	70	74	78	93	88
2950BC	79	77	82	86	90	77	65	69	62	74
	74	71	64	75	79	79	96	98	82	92
	92	91	92	87	86	87	96	87	78	72
	98	94	84	89	75	69	53	71	73	65
	48									

7.10 Appendix X: Moving correlation function analysis

Mallaig showed no consistent correlation and is not shown.

Figure 150: Moving correlation functions - Abernethy A.

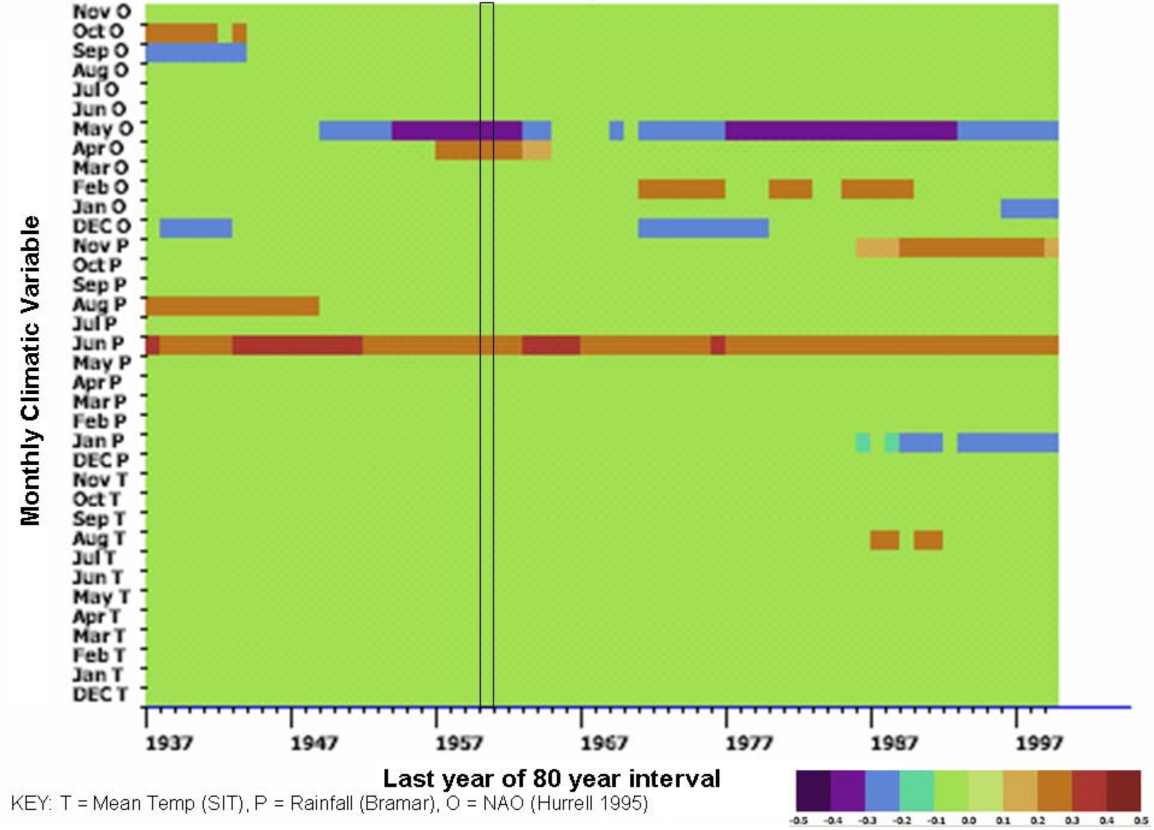


Figure 151: Moving correlation functions - Abernethy B

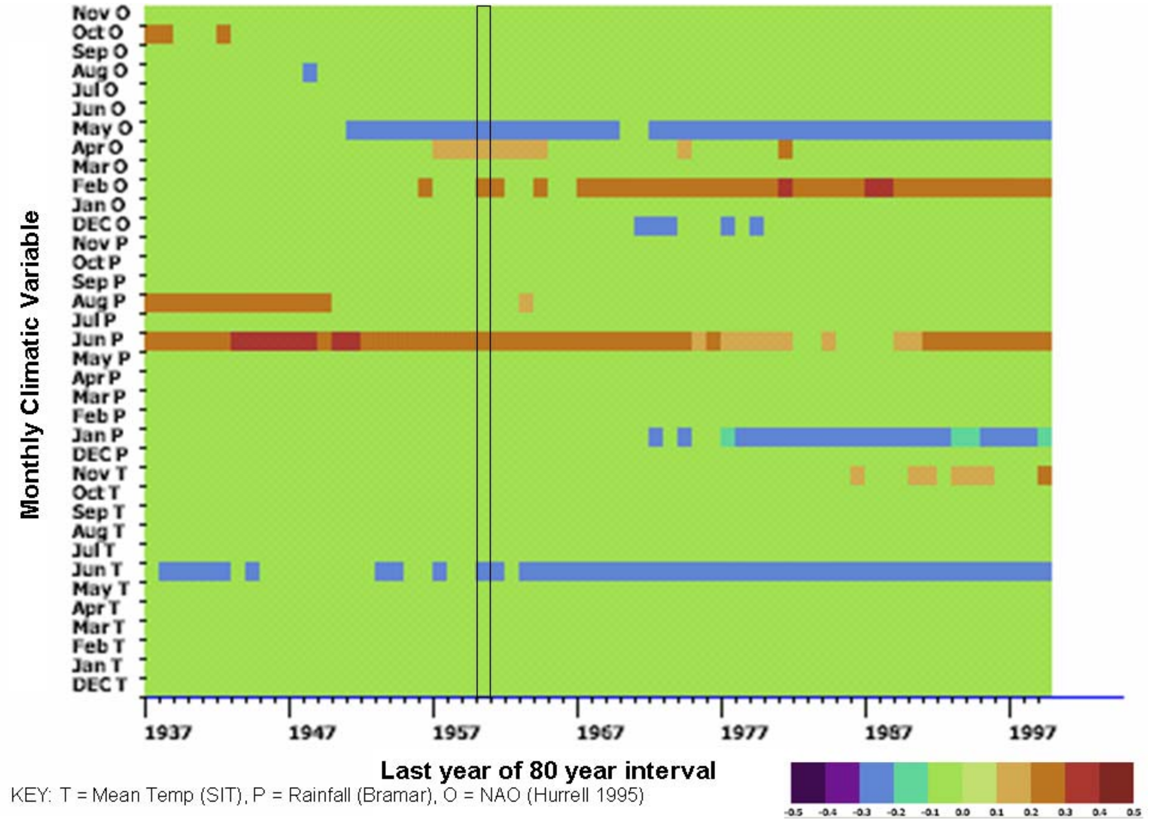


Figure 152: Moving correlation functions - Abernethy C.

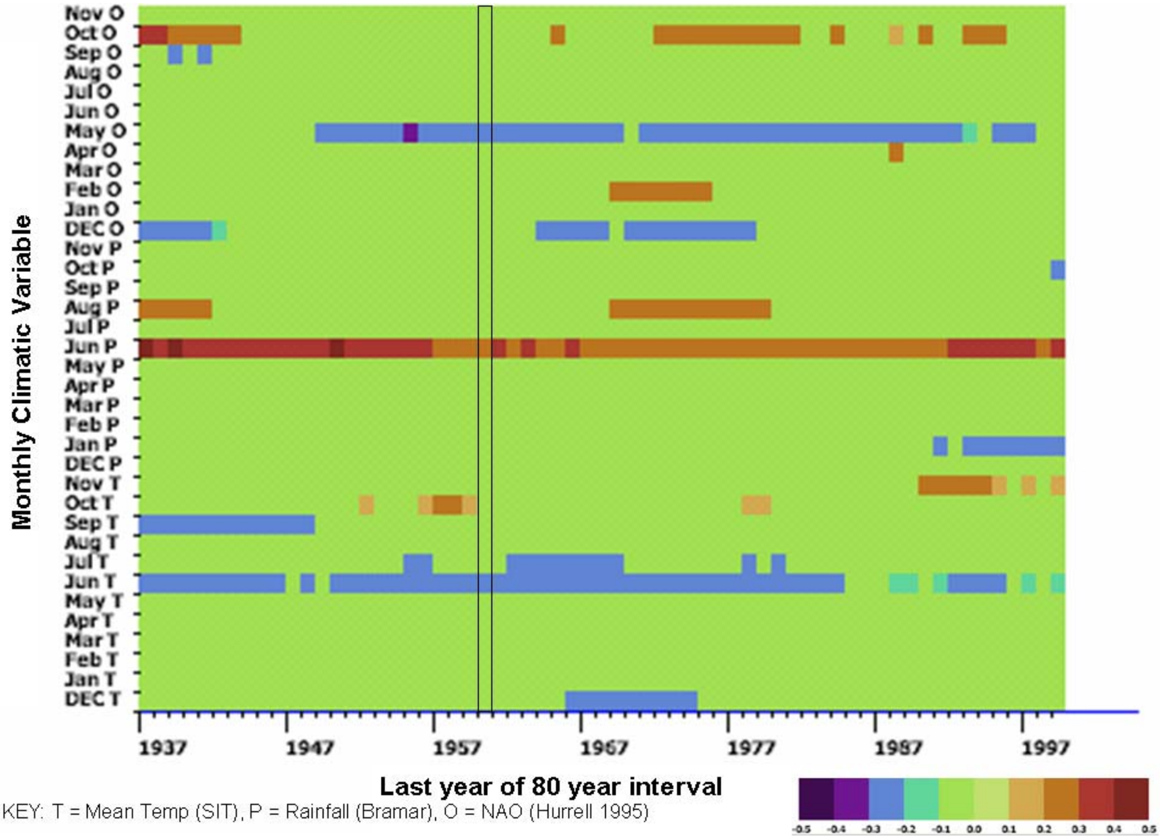


Figure 153: Moving correlation functions - Abernethy D.

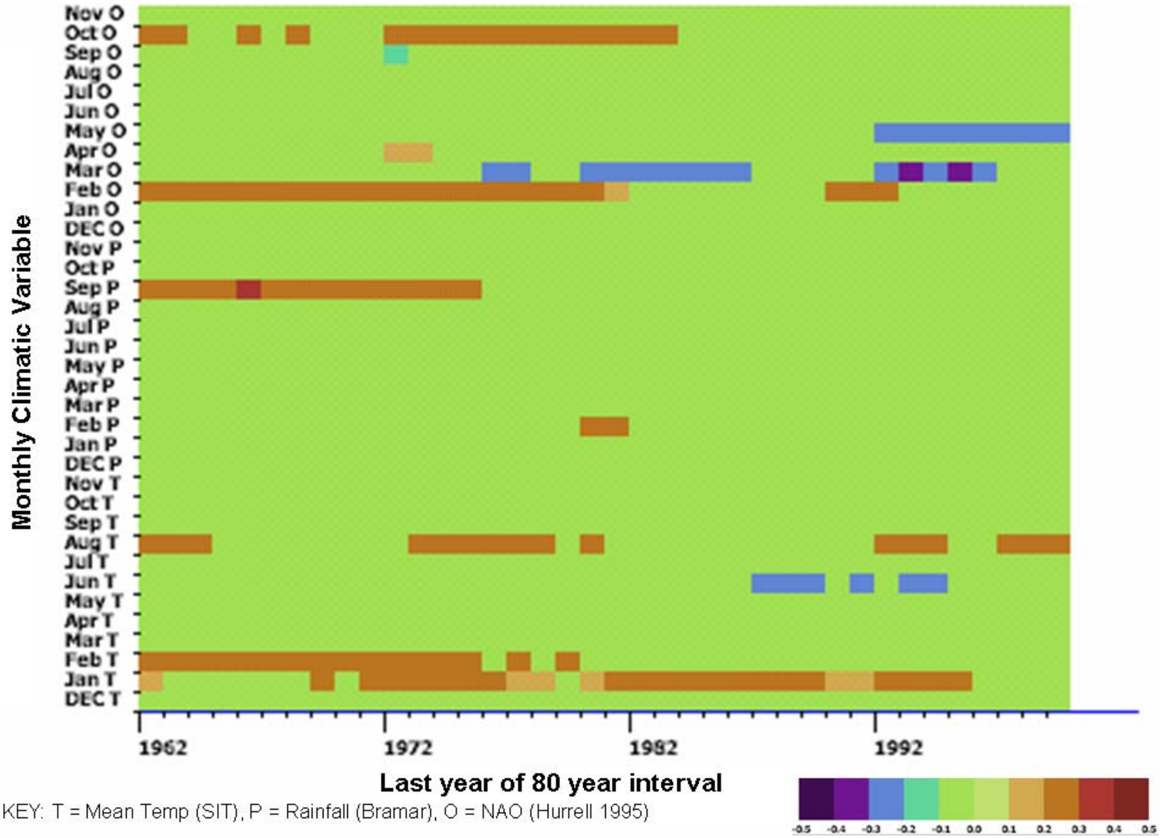
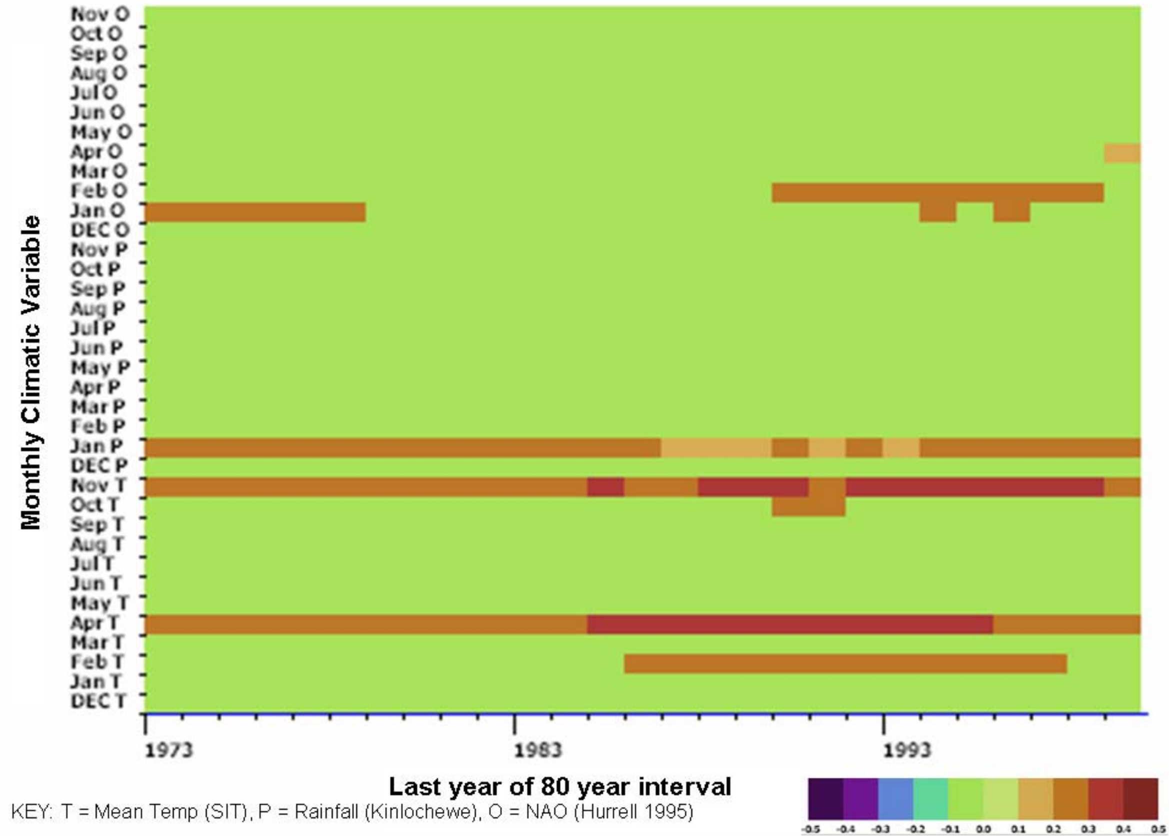
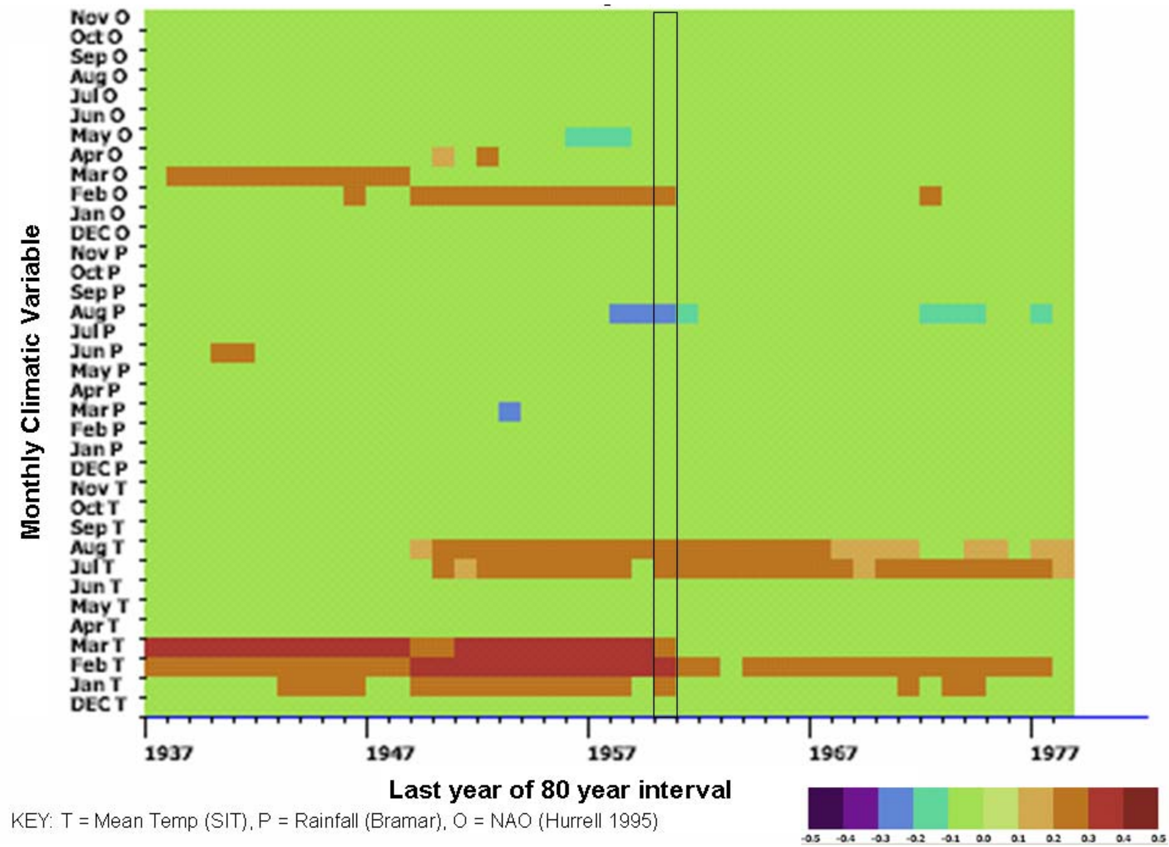


Figure 154: Moving correlation functions – Achanalt.



KEY: T = Mean Temp (SIT), P = Rainfall (Kinlochewe), O = NAO (Hurrell 1995)

Figure 155: Moving correlation functions – Ballochbuie.



KEY: T = Mean Temp (SIT), P = Rainfall (Bramar), O = NAO (Hurrell 1995)

Figure 156: Moving correlation functions - Beinn Eighe.

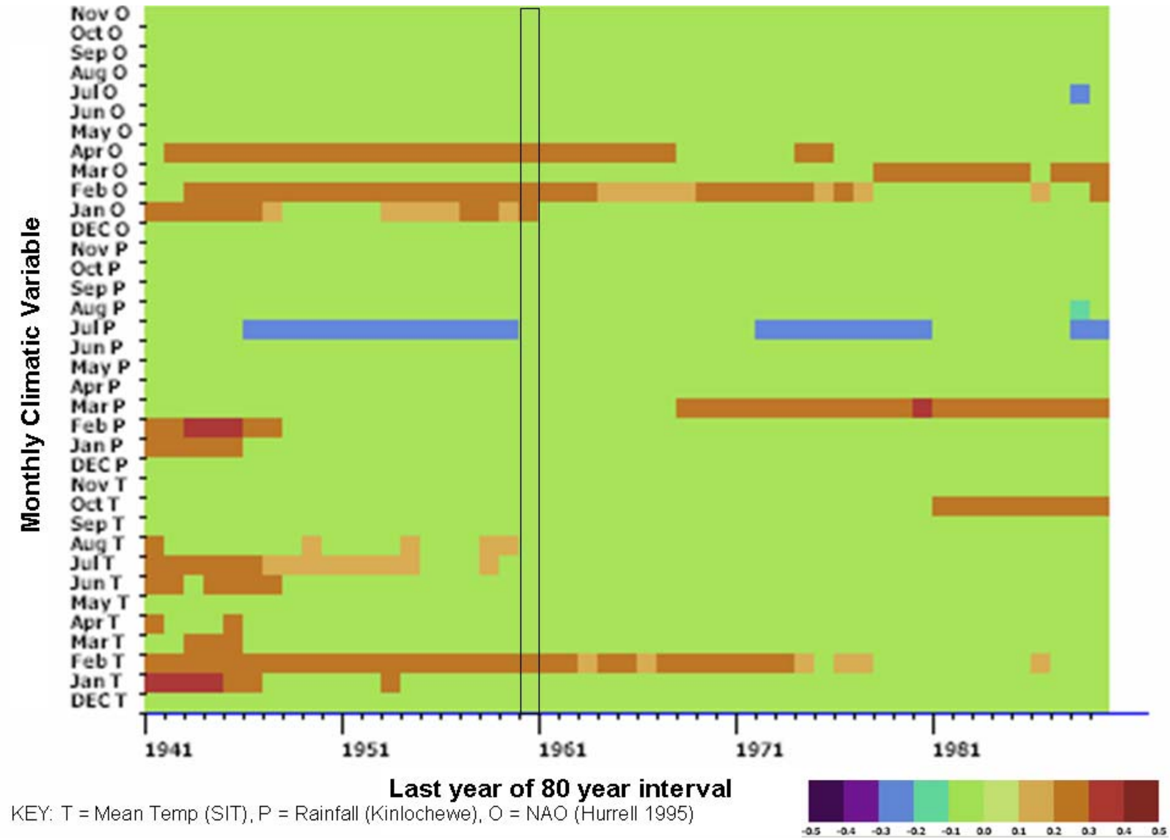


Figure 157: Moving correlation functions – Carrbridge.

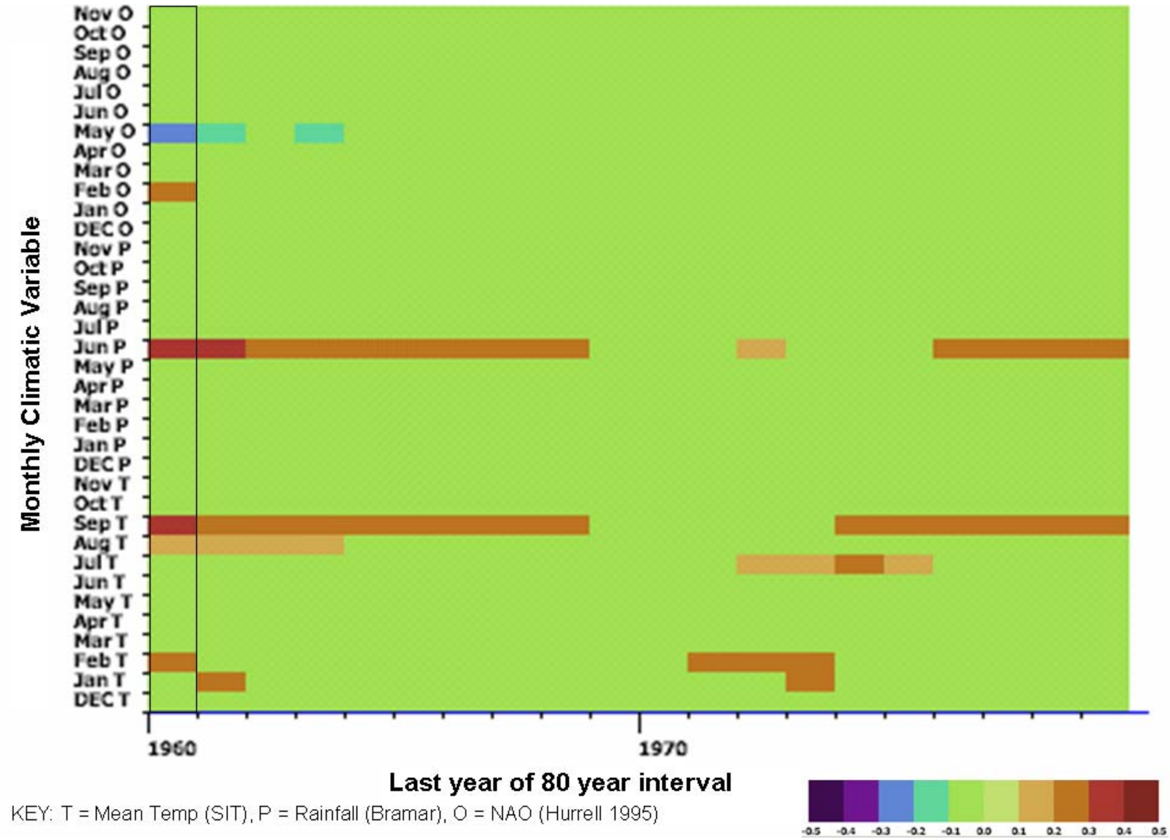


Figure 158: Moving correlation functions – Coulin.

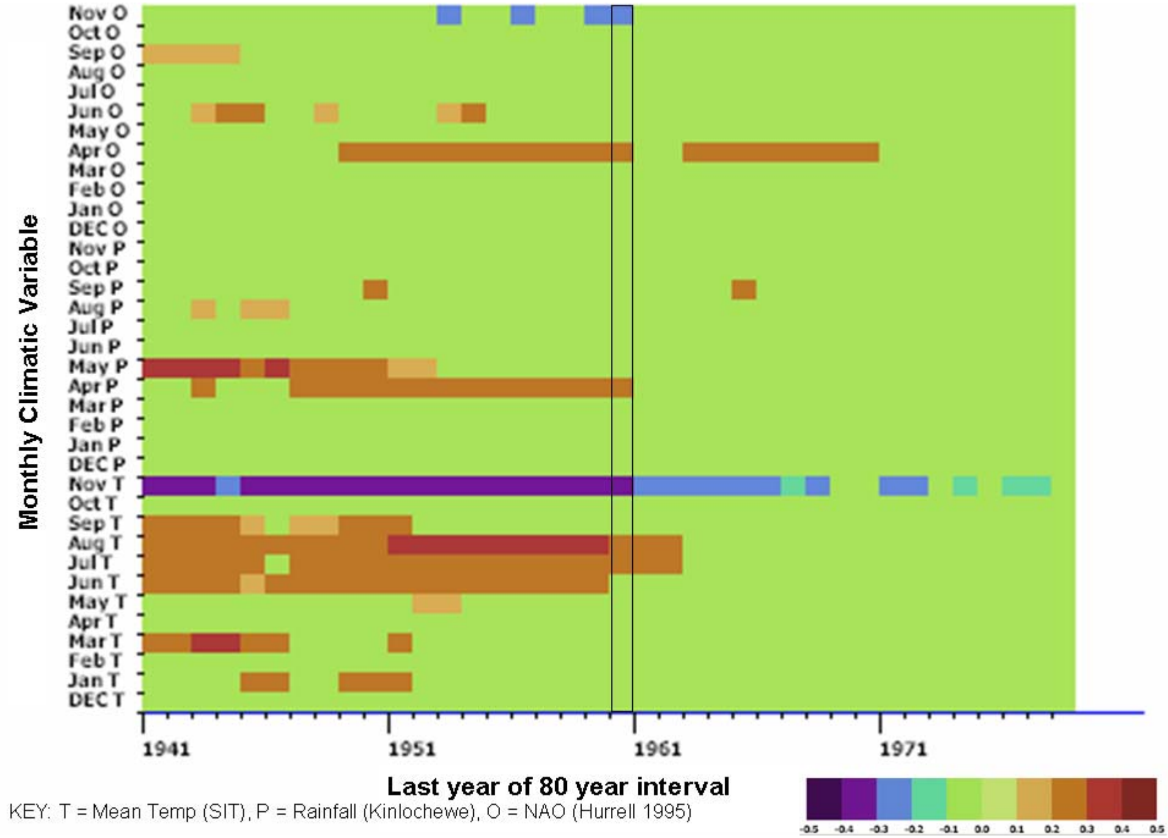


Figure 159: Moving correlation functions - Creag Fhiaclach A

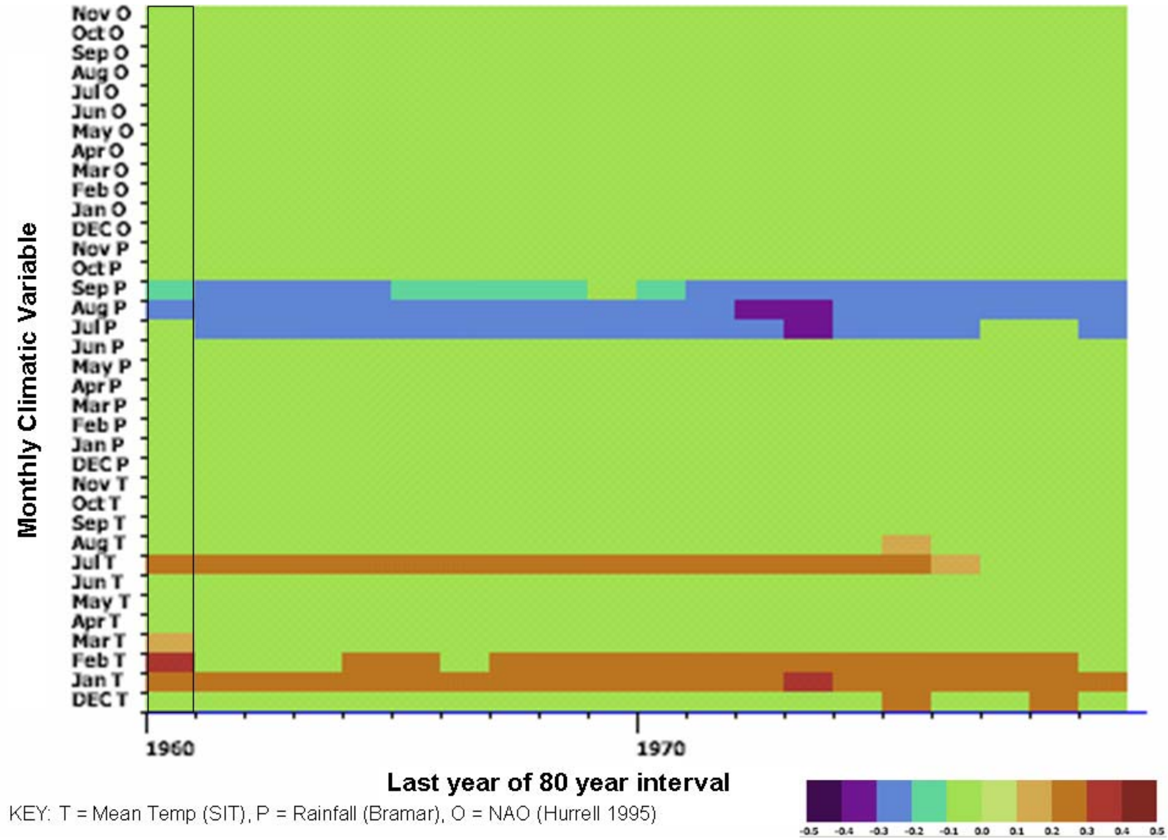


Figure 160: Moving correlation functions - Creag Fhiaclach B.

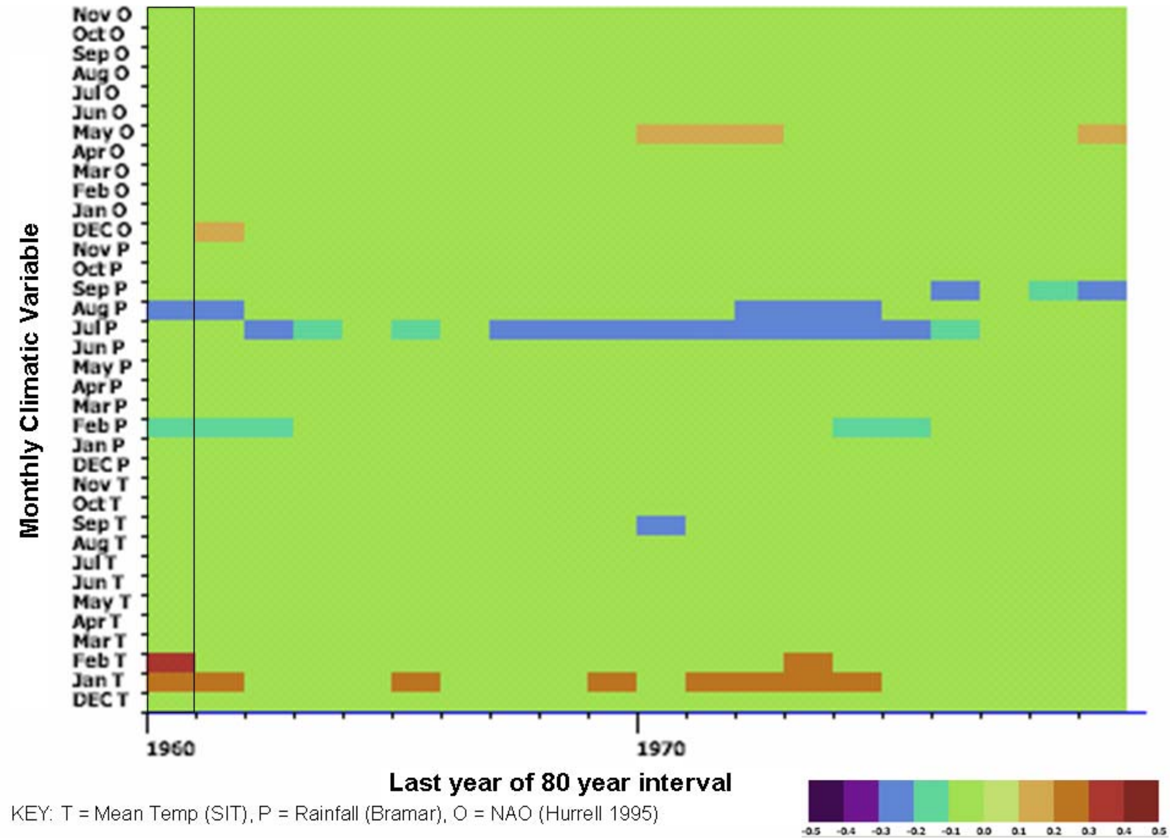


Figure 161: Moving correlation functions - Creag Fhiaclach D.

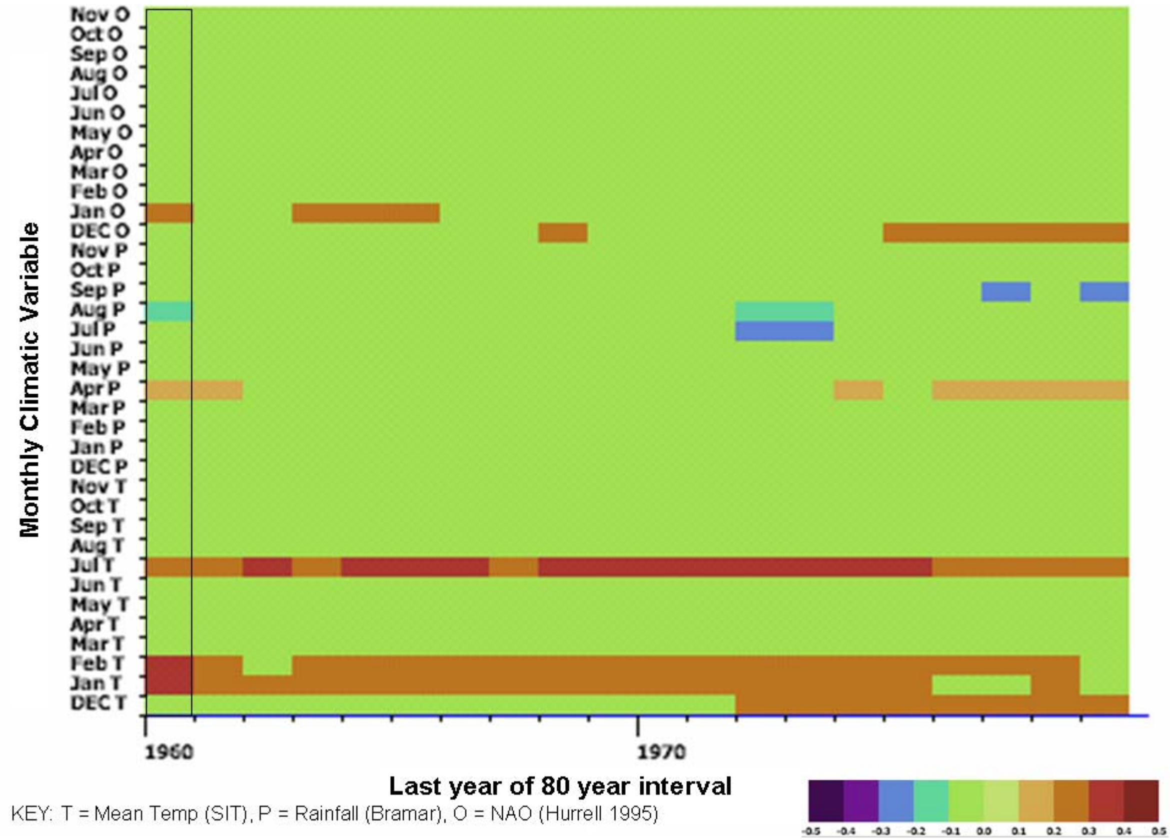


Figure 162: Moving correlation functions - Creag Fhiaclach E.

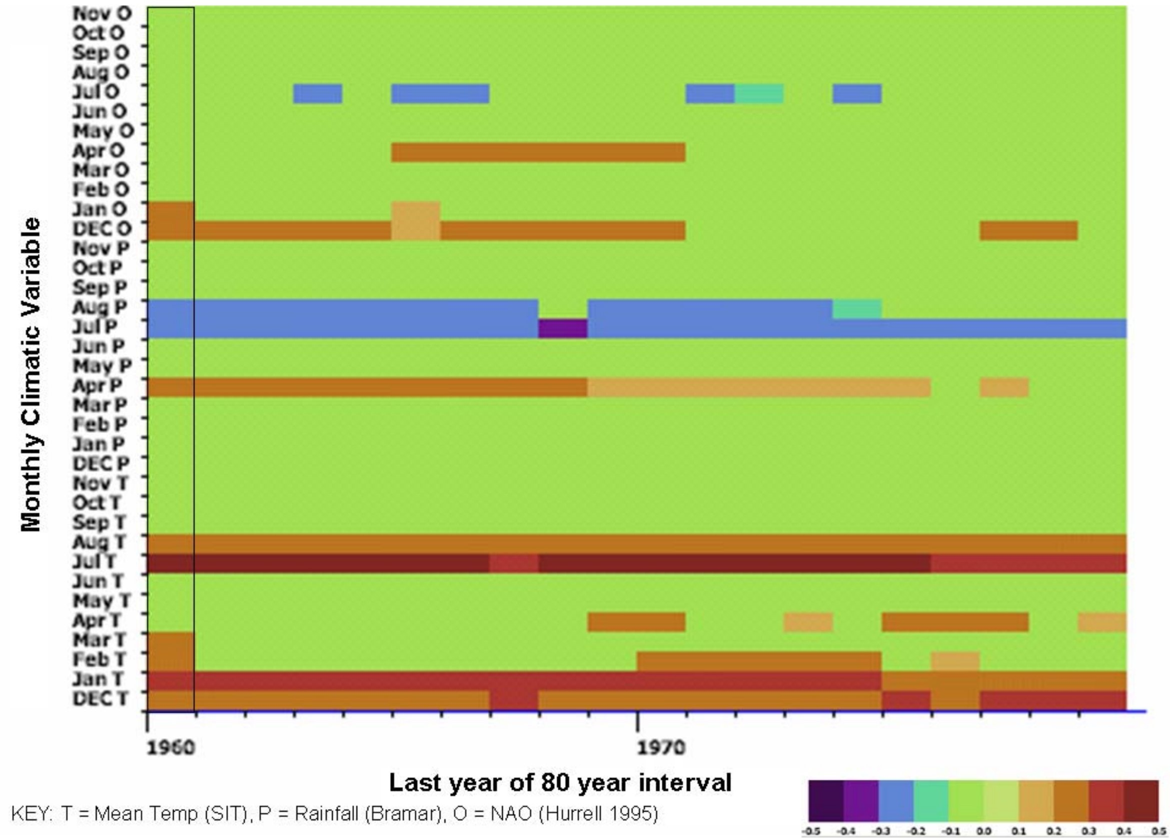


Figure 163: Moving correlation functions - Creag Fhiaclach F.

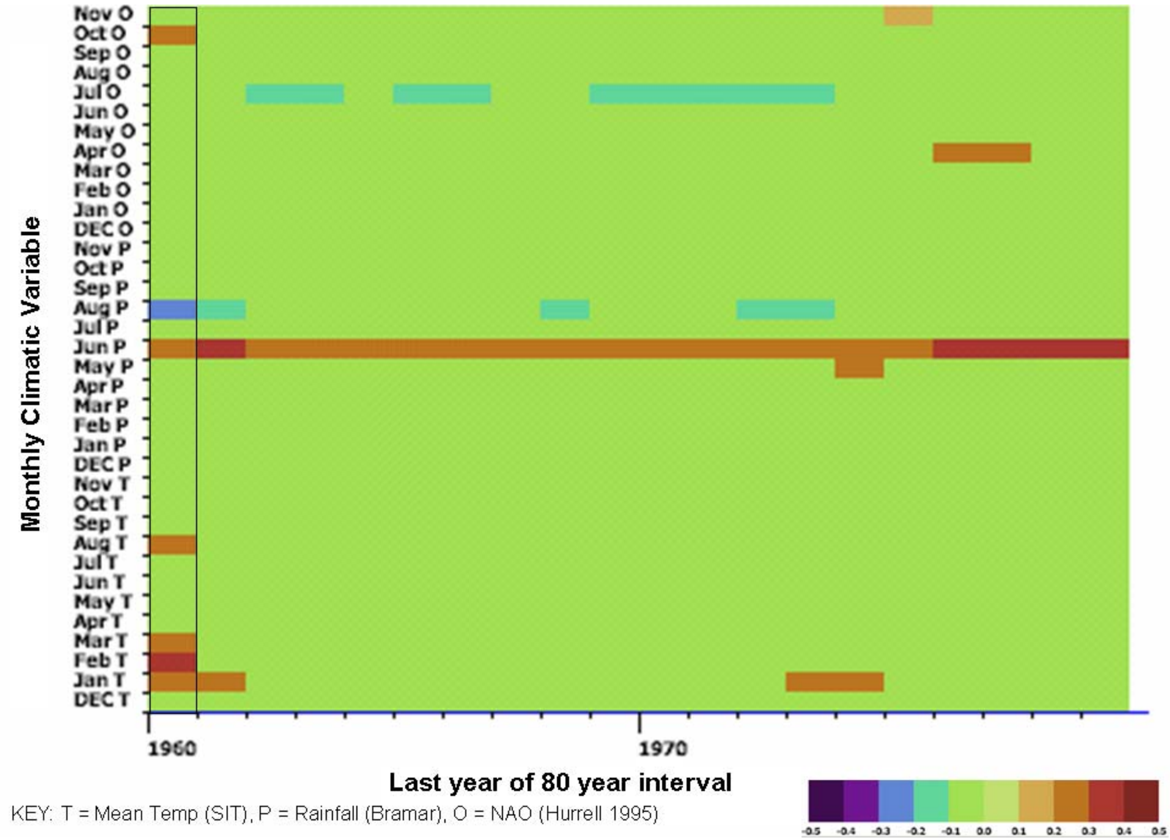
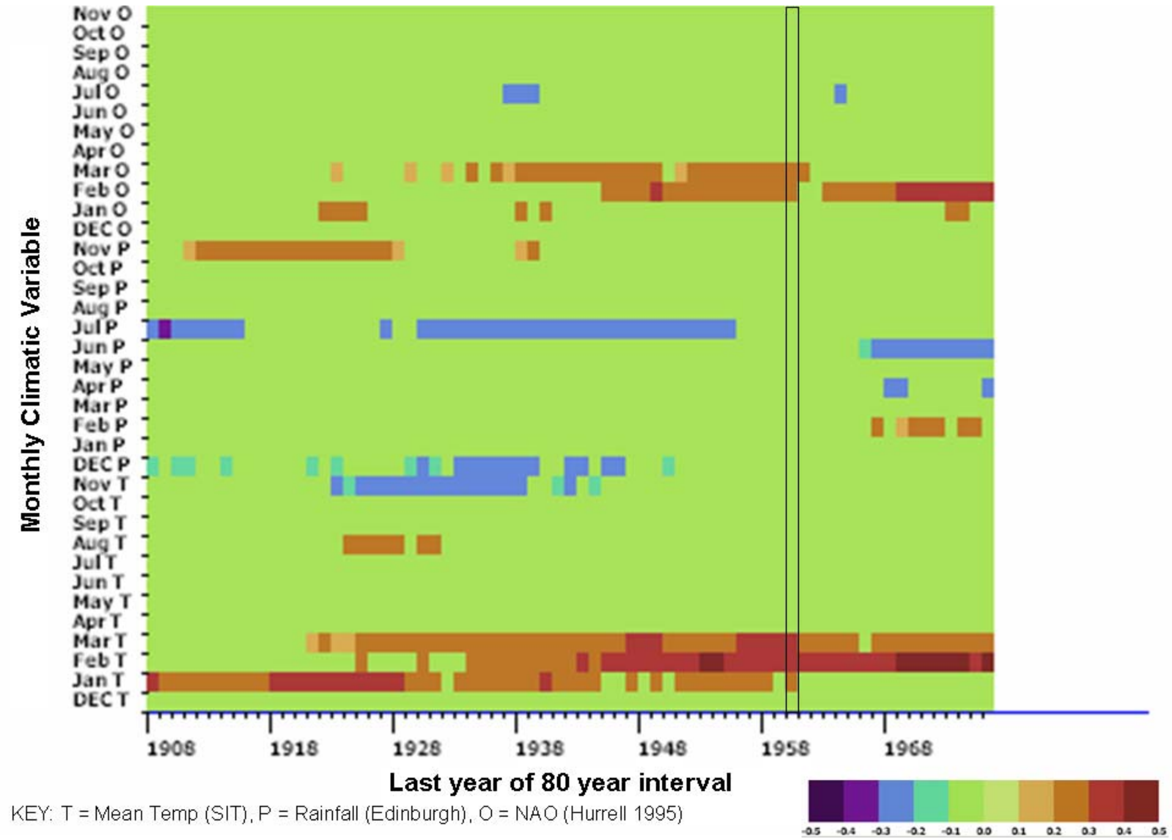
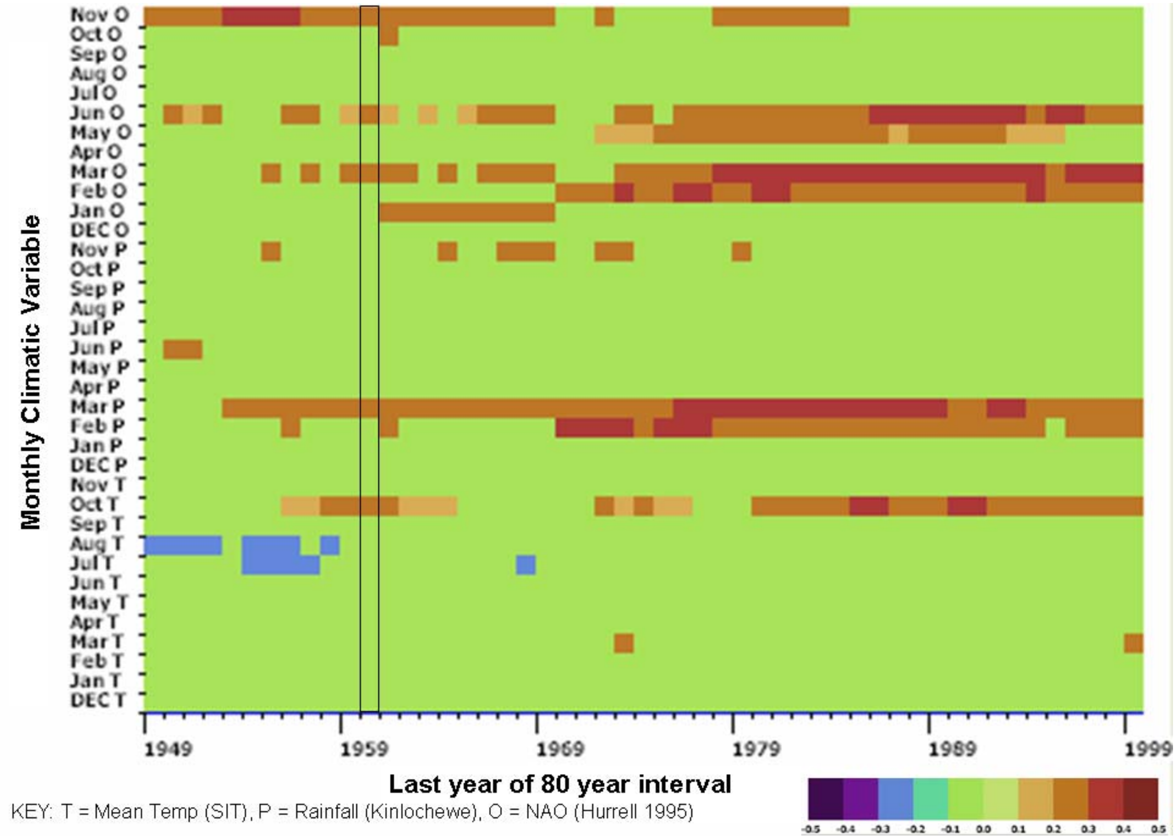


Figure 164: Moving correlation functions – Dimmie.



KEY: T = Mean Temp (SIT), P = Rainfall (Edinburgh), O = NAO (Hurrell 1995)

Figure 165: Moving correlation functions - Eilann Sùbhainn A.



KEY: T = Mean Temp (SIT), P = Rainfall (Kinlochewe), O = NAO (Hurrell 1995)

Figure 166: Moving correlation functions - Eilann Sùbhainn B.

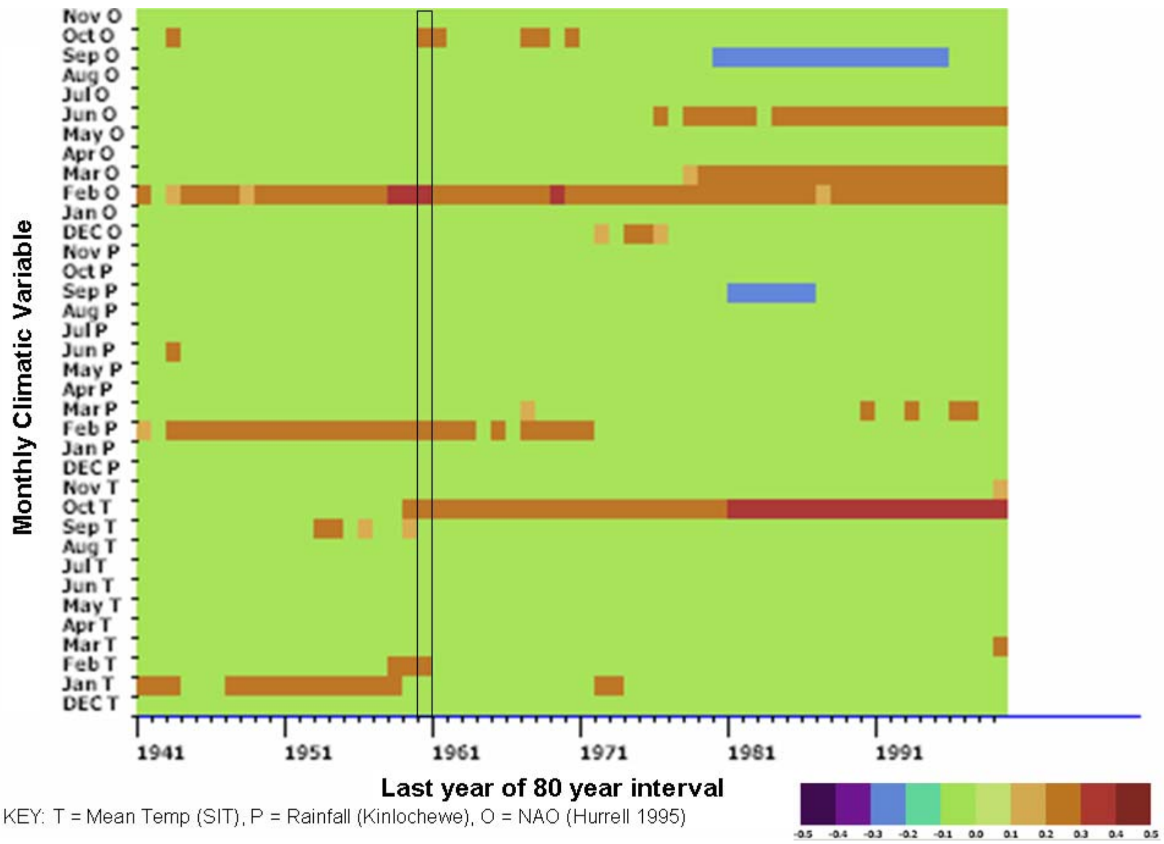


Figure 167: Moving correlation functions - Eilann Sùbhainn C.

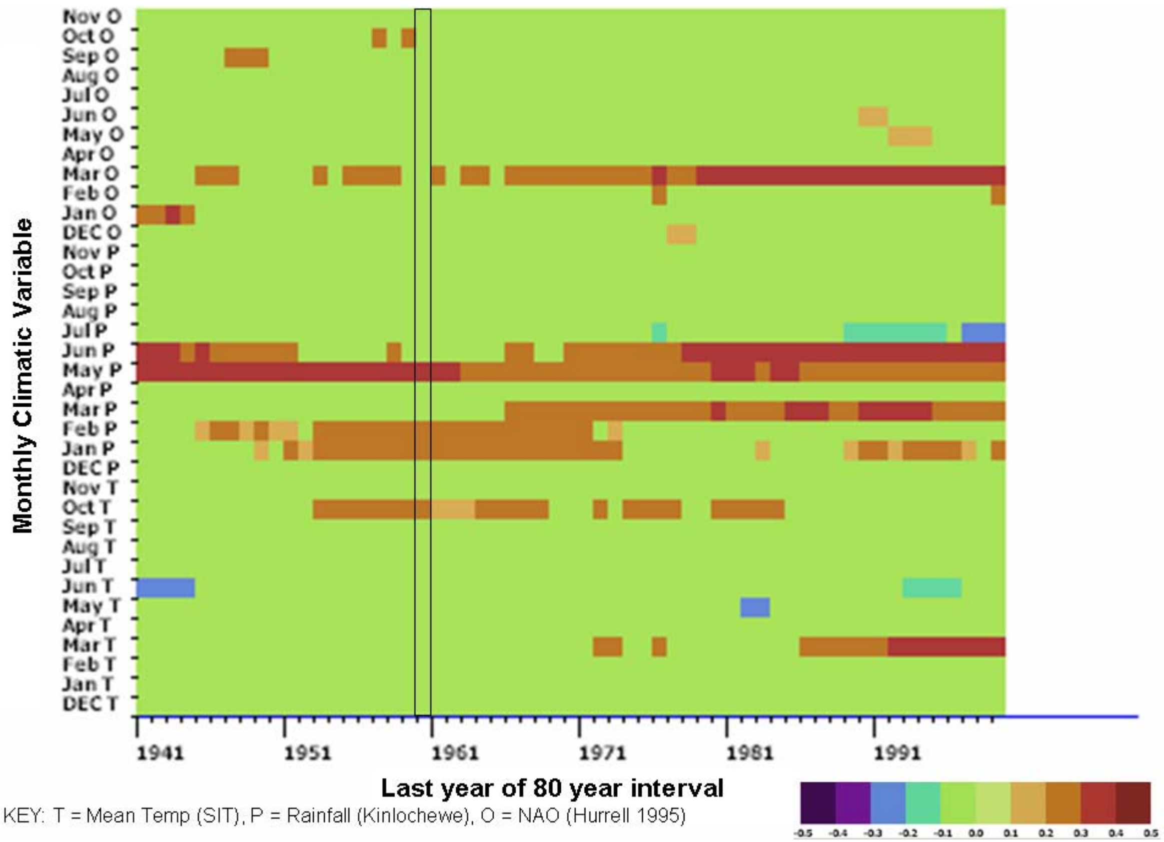


Figure 168: Moving correlation functions - Glen Affric.

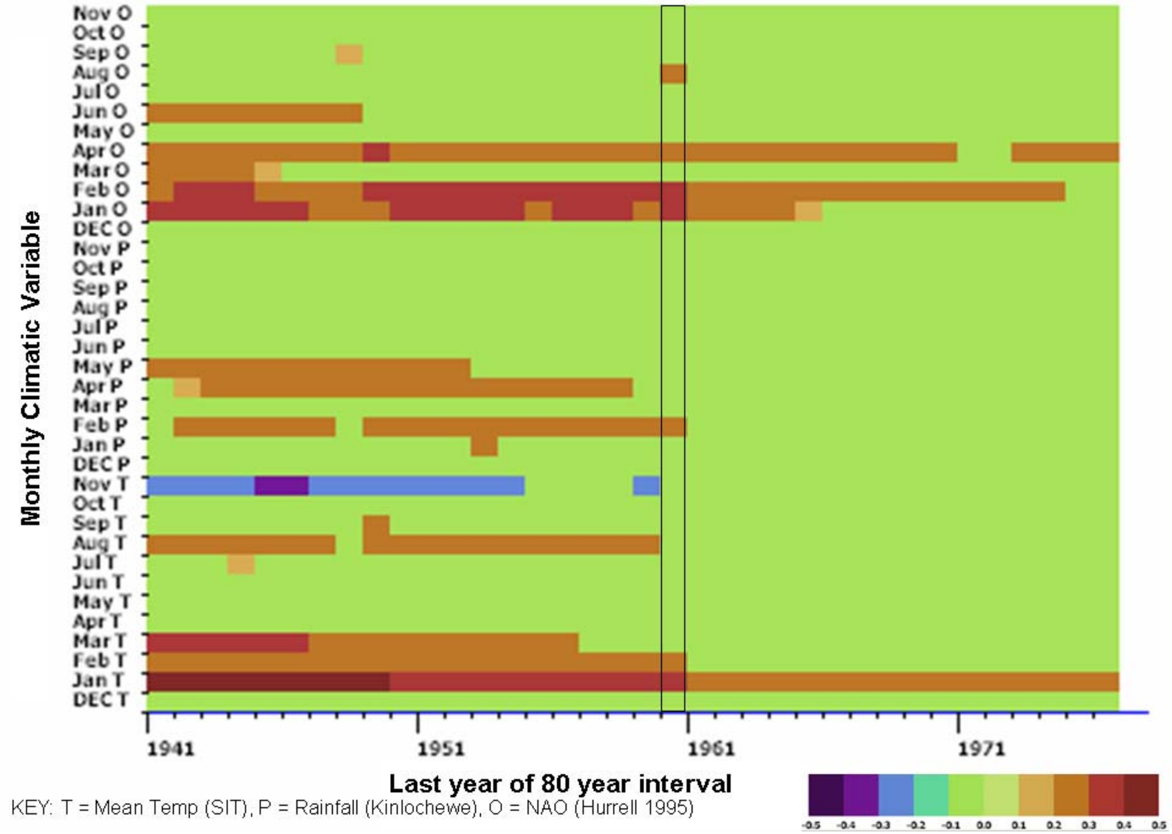


Figure 169: Moving correlation functions - Glen Derry.

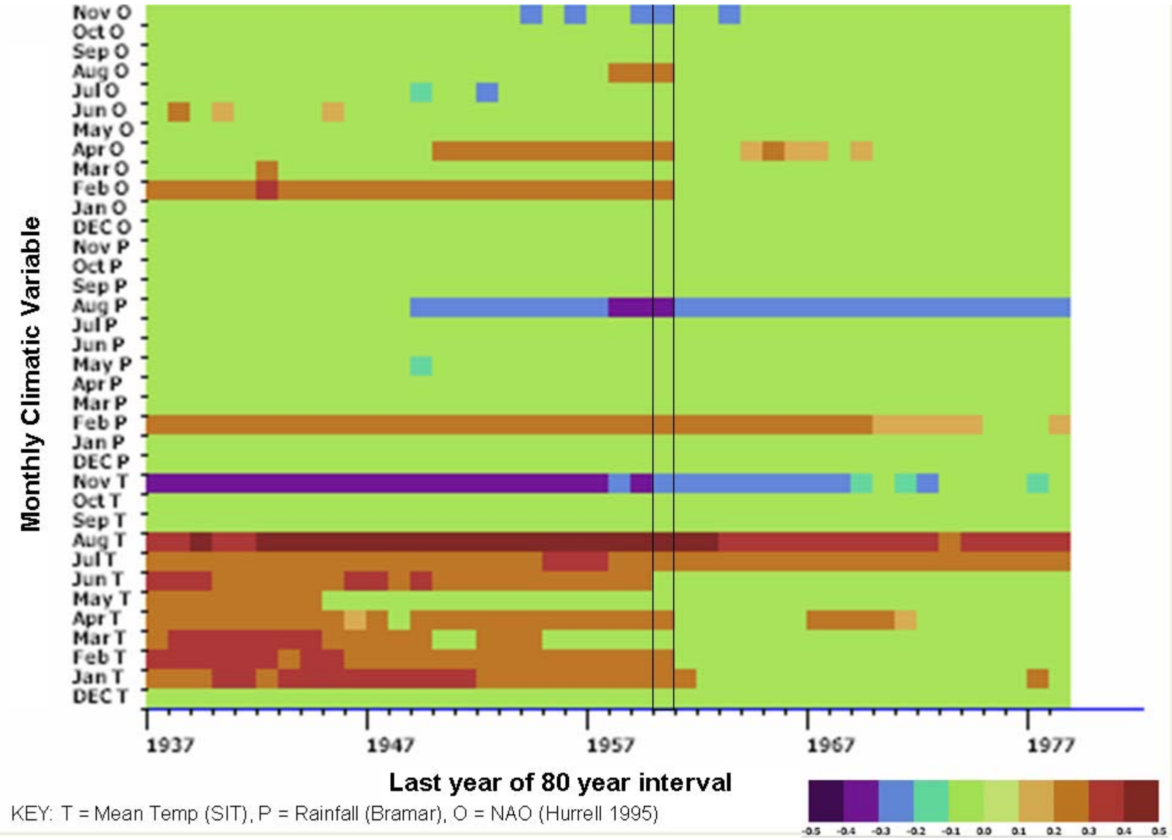
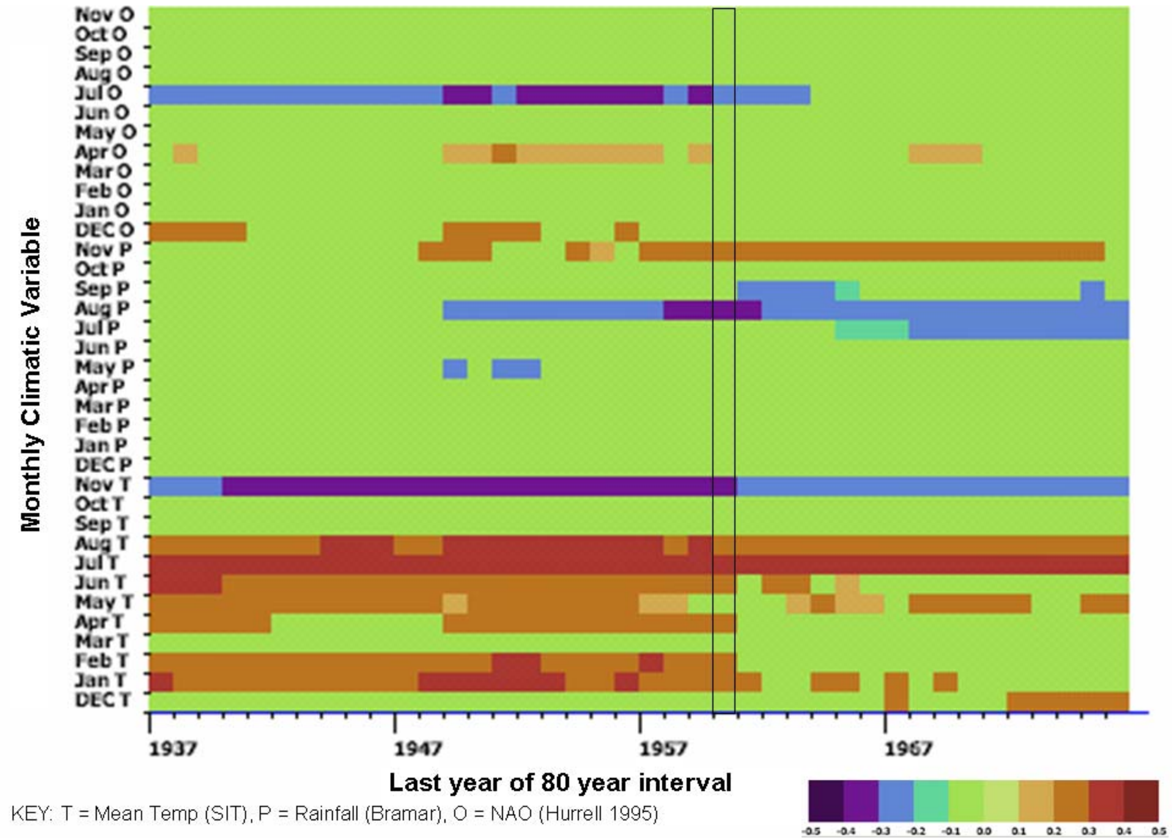
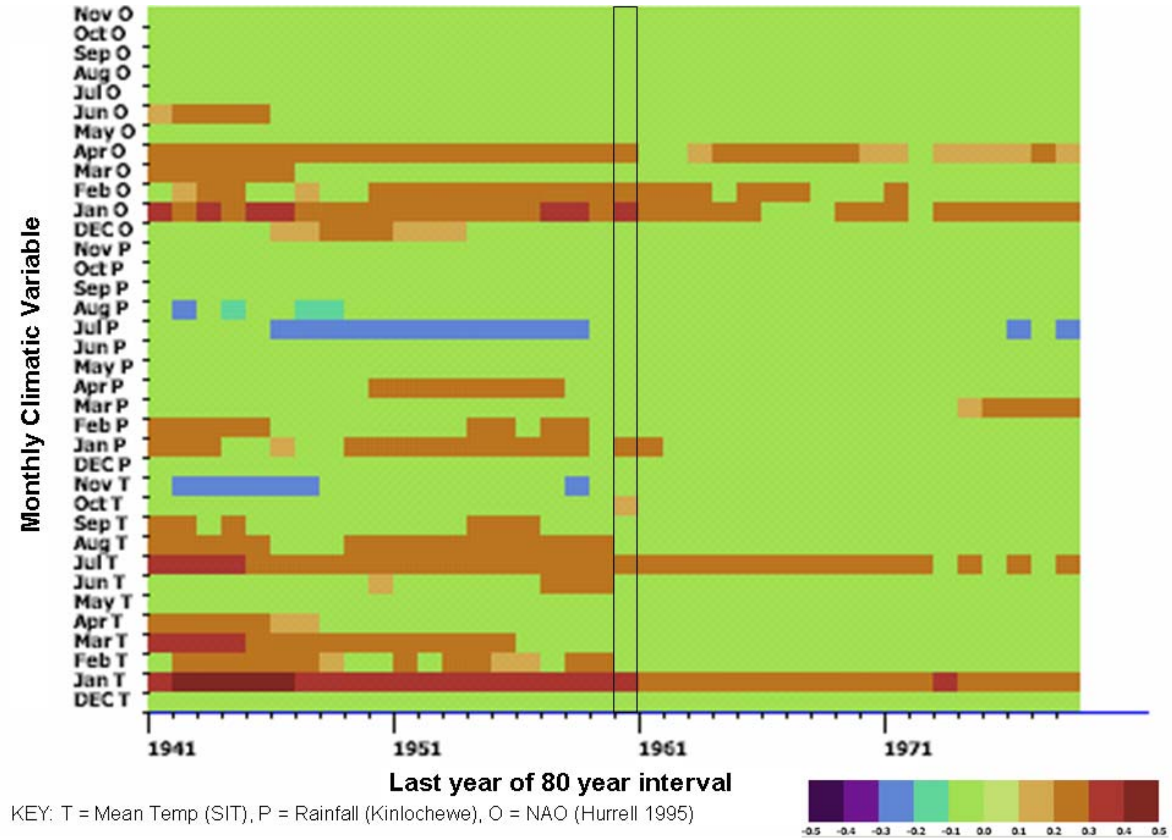


Figure 170: Moving correlation functions – Inverey.



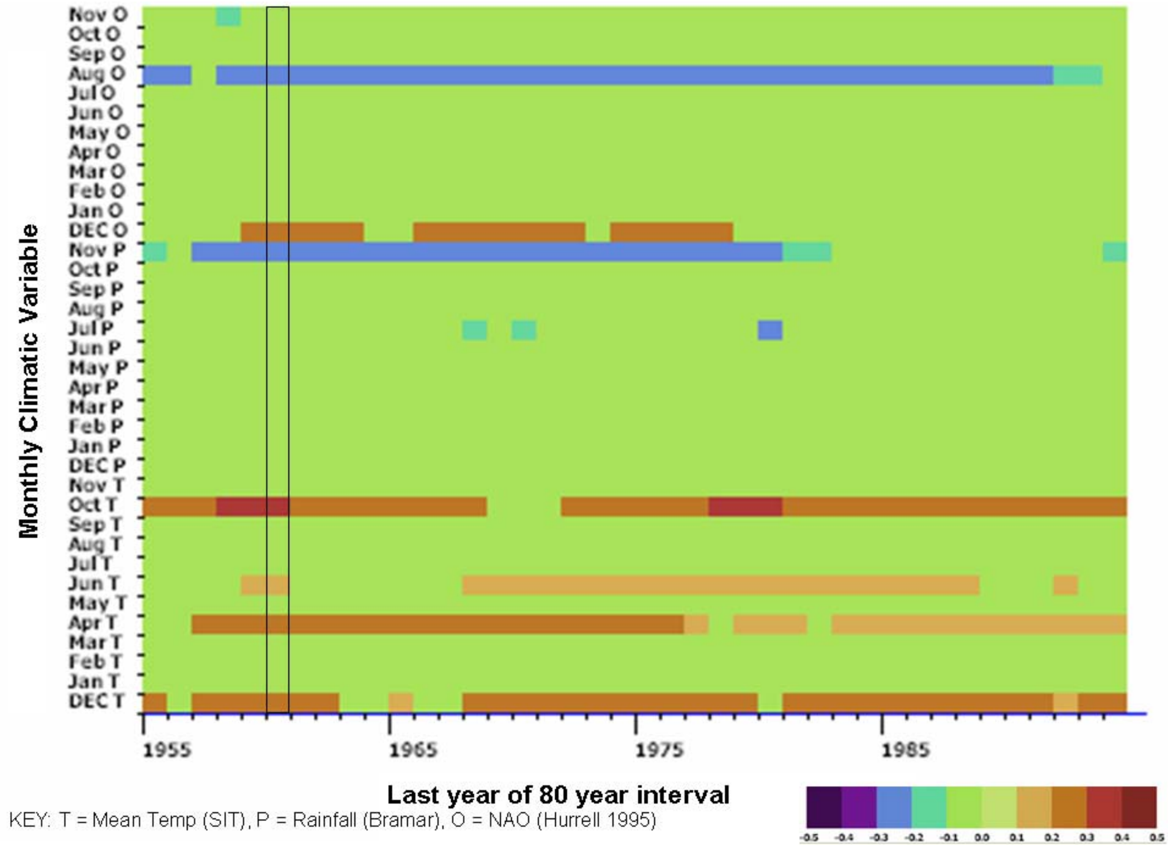
KEY: T = Mean Temp (SIT), P = Rainfall (Bramar), O = NAO (Hurrell 1995)

Figure 171: Moving correlation functions - Loch Maree.



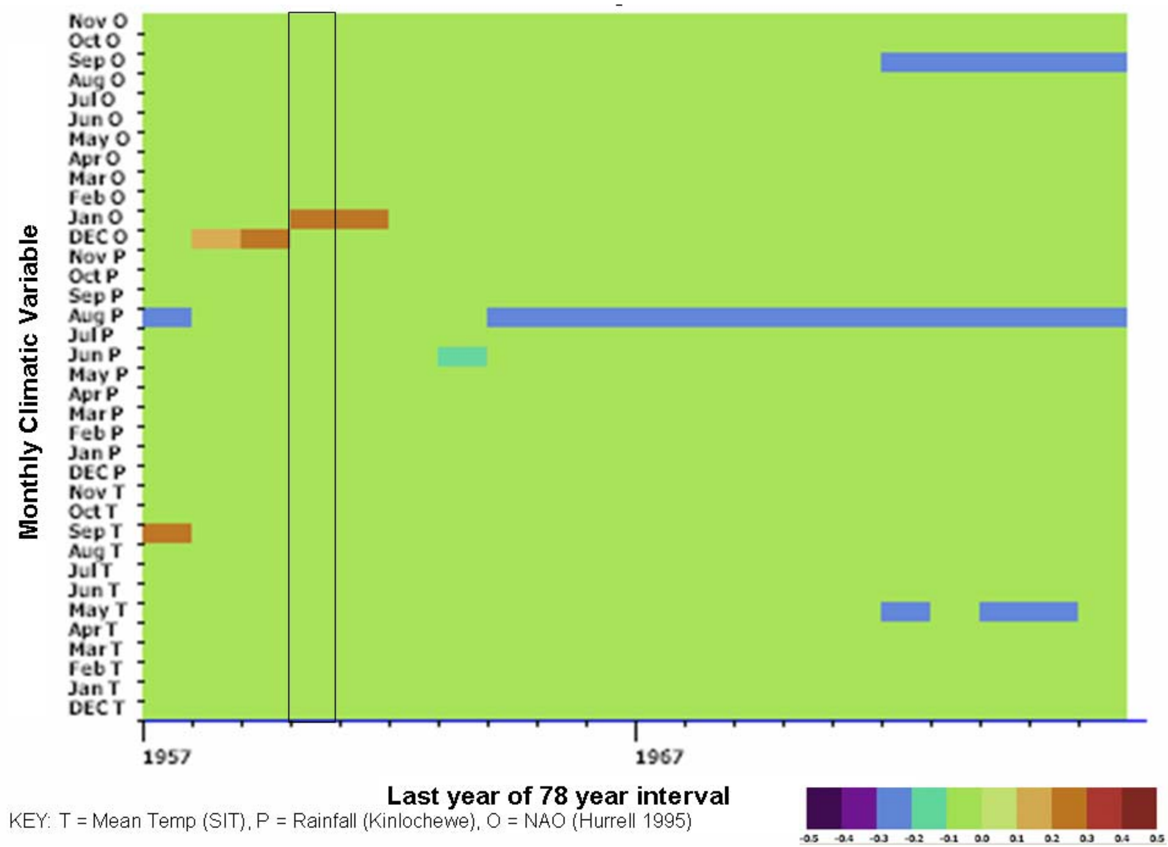
KEY: T = Mean Temp (SIT), P = Rainfall (Kinlochewe), O = NAO (Hurrell 1995)

Figure 172: Moving correlation functions - Pitmaduthy A.



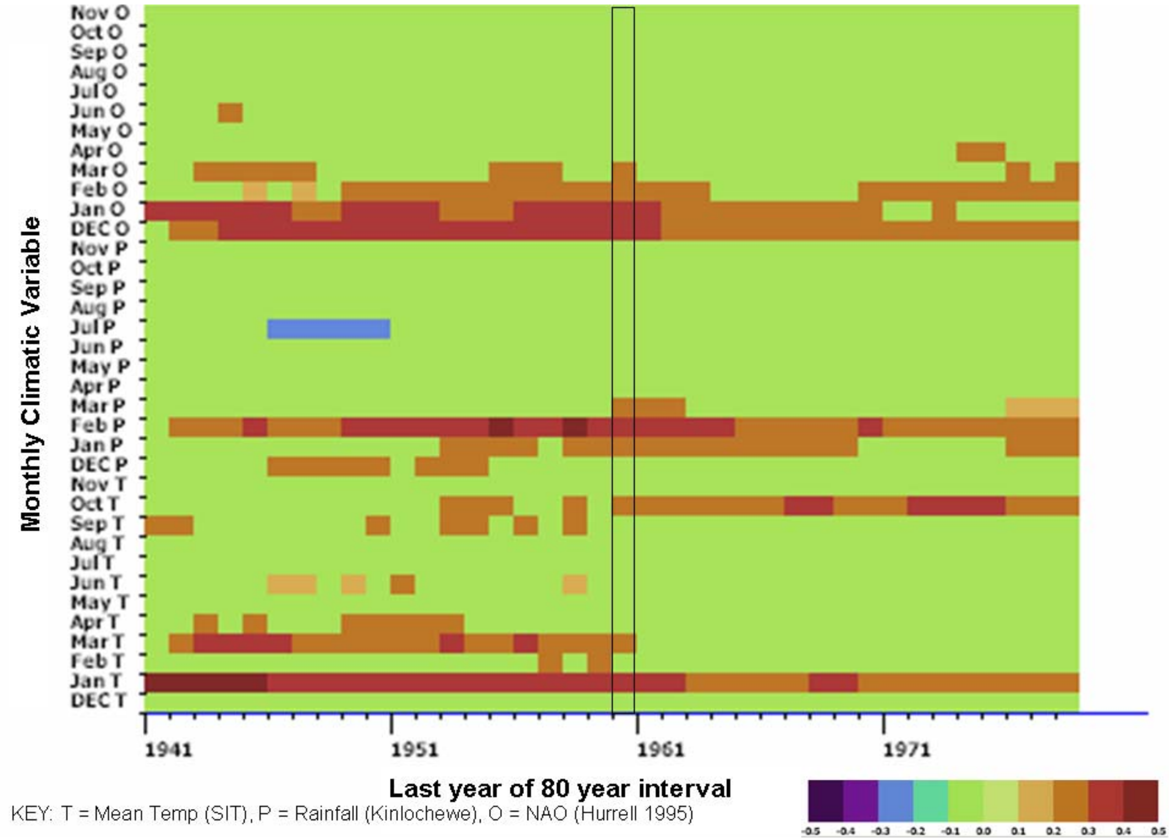
KEY: T = Mean Temp (SIT), P = Rainfall (Bramar), O = NAO (Hurrell 1995)

Figure 173: Moving correlation functions – Plockton.



KEY: T = Mean Temp (SIT), P = Rainfall (Kinlochewe), O = NAO (Hurrell 1995)

Figure 174: Moving correlation functions – Shieldaig.



KEY: T = Mean Temp (SIT), P = Rainfall (Kinlochewe), O = NAO (Hurrell 1995)

7.11 Appendix XI: Pearsons correlation for BORAL-PN & OCEAN-PN regional chronologies.

Pearson Correlation Results for: 1881-1930

Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
SIT-JanT	40.660	11.587	1.639	50
SIT-FebT	37.760	11.909	1.684	50
SIT-JulyT	119.960	8.471	1.198	50
SIT-AugT	120.520	9.410	1.331	50
SMT-JanT	23.980	15.244	2.156	50
SMT-FebT	24.440	15.348	2.171	50
SMT-JulyT	123.600	9.187	1.299	50
SMT-AugT	121.260	9.245	1.307	50
Bre-AugR	878.080	383.417	54.223	50
NAO-Feb	0.999	2.077	0.294	50
POINT-YR	99.000	29.433	4.163	50
BORAL-PN	111.340	13.230	1.871	50
OCEAN-PN	161.420	36.083	5.103	50
BORAL-BP	58.760	14.264	2.017	50
OCEAN-BP	99.980	27.427	3.879	50

Correlation Matrix (R)

	SIT-JanT	SIT-FebT	SIT-JulyT	SIT-AugT	SMT-JanT	SMT-FebT	SMT-JulyT	SMT-AugT	Bre-AugR	NAO-Feb	POINT-YR	BORAL-PN	OCEAN-PN	BORAL-BP
SIT-JanT	1.000	0.330	0.101	0.059	0.931	0.319	0.226	0.073	-0.180	0.210	0.232	0.368	-0.088	0.033
SIT-FebT	0.330	1.000	0.283	0.132	0.368	0.889	0.292	0.143	-0.221	0.605	0.299	0.339	-0.152	-0.231
SIT-JulyT	0.101	0.283	1.000	0.609	0.084	0.238	0.848	0.524	-0.014	0.205	0.491	0.466	0.049	-0.027
SIT-AugT	0.059	0.132	0.609	1.000	0.079	0.032	0.429	0.879	-0.026	0.109	0.363	0.430	-0.088	0.162
SMT-JanT	0.931	0.368	0.084	0.079	1.000	0.374	0.194	0.130	-0.163	0.260	0.250	0.368	-0.043	0.069
SMT-FebT	0.319	0.889	0.238	0.032	0.374	1.000	0.210	0.056	-0.158	0.734	0.310	0.302	0.005	-0.100
SMT-JulyT	0.226	0.292	0.848	0.429	0.194	0.210	1.000	0.467	-0.048	0.109	0.398	0.431	0.012	-0.085
SMT-AugT	0.073	0.143	0.524	0.879	0.130	0.056	0.467	1.000	-0.239	0.137	0.350	0.383	0.035	0.110
Bre-AugR	-0.180	-0.221	-0.014	-0.026	-0.163	-0.158	-0.048	-0.239	1.000	-0.001	-0.221	-0.169	-0.124	0.163
NAO-Feb	0.210	**0.605**	0.205	0.109	0.260	**0.734**	0.109	0.137	-0.001	1.000	0.258	0.189	-0.021	-0.117
POINT-YR	0.232	0.299	0.491	0.363	0.250	0.310	0.398	0.350	-0.221	0.258	1.000	0.651	0.121	0.016
BORAL-PN	**0.368**	**0.339**	**0.466**	**0.430**	**0.368**	**0.302**	**0.431**	**0.383**	-0.169	0.189	**0.651**	1.000	-0.167	0.204
OCEAN-PN	-0.088	-0.152	0.049	-0.088	-0.043	0.005	0.012	0.035	-0.124	-0.021	0.121	-0.167	1.000	0.142
BORAL-BP	0.033	-0.231	-0.027	0.162	0.069	-0.100	-0.085	0.110	0.163	-0.117	0.016	0.204	0.142	1.000
OCEAN-BP	-0.167	-0.062	-0.081	-0.199	-0.113	0.057	-0.111	-0.097	-0.165	-0.012	0.008	**-0.328**	**0.657**	0.029

t Statistic

	SIT-JanT	SIT-FebT	SIT-JulyT	SIT-AugT	SMT-JanT	SMT-FebT	SMT-JulyT	SMT-AugT	Bre-AugR	NAO-Feb	POINT-YR	BORAL-PN	OCEAN-PN	BORAL-BP
SIT-JanT	-	2.425	0.701	0.409	17.710	2.332	1.611	0.505	1.271	1.486	1.655	2.742	0.611	0.228
SIT-FebT	2.425	-	2.045	0.921	2.738	13.479	2.115	0.998	1.570	5.270	2.172	2.495	1.064	1.641
SIT-JulyT	0.701	2.045	-	5.325	0.586	1.695	11.079	4.265	0.097	1.454	3.904	3.654	0.342	0.190
SIT-AugT	0.409	0.921	5.325	-	0.552	0.223	3.288	12.751	0.182	0.759	2.699	3.301	0.612	1.134
SMT-JanT	17.710	2.738	0.586	0.552	-	2.790	1.367	0.909	1.145	1.869	1.790	2.739	0.296	0.482
SMT-FebT	2.332	13.479	1.695	0.223	2.790	-	1.491	0.386	1.110	7.484	2.263	2.198	0.038	0.696
SMT-JulyT	1.611	2.115	11.079	3.288	1.367	1.491	-	3.663	0.336	0.757	3.010	3.313	0.086	0.590
SMT-AugT	0.505	0.998	4.265	12.751	0.909	0.386	3.663	-	1.707	0.957	2.586	2.871	0.241	0.769
Bre-AugR	1.271	1.570	0.097	0.182	1.145	1.110	0.336	1.707	-	0.005	1.566	1.185	0.866	1.144
NAO-Feb	1.486	**5.270**	1.454	0.759	1.869	**7.484**	0.757	0.957	0.005	-	1.850	1.336	0.147	0.815
POINT-YR	1.655	2.172	3.904	2.699	1.790	2.263	3.010	2.586	1.566	1.850	-	5.938	0.848	0.114
BORAL-PN	**2.742**	**2.495**	**3.654**	**3.301**	**2.739**	**2.198**	**3.313**	**2.871**	1.185	1.336	**5.938**	-	1.176	1.446
OCEAN-PN	0.611	1.064	0.342	0.612	0.296	0.038	0.086	0.241	0.866	0.147	0.848	1.176	-	0.997
BORAL-BP	0.228	1.641	0.190	1.134	0.482	0.696	0.590	0.769	1.144	0.815	0.114	1.446	0.997	-
OCEAN-BP	1.171	0.433	0.563	1.410	0.788	0.398	0.777	0.673	1.158	0.082	0.052	**2.405**	**6.039**	0.201

Correlation Significance (P)

	SIT-JanT	SIT-FebT	SIT-JulyT	SIT-AugT	SMT-JanT	SMT-FebT	SMT-JulyT	SMT-AugT	Bre-AugR	NAO-Feb	POINT-YR	BORAL-PN	OCEAN-PN	BORAL-BP
SIT-JanT	-	0.019	0.487	0.684	0.000	0.024	0.114	0.616	0.210	0.144	0.104	0.009	0.544	0.821
SIT-FebT	0.019	-	0.046	0.362	0.009	0.000	0.040	0.323	0.123	0.000	0.035	0.016	0.293	0.107
SIT-JulyT	0.487	0.046	-	0.000	0.561	0.097	0.000	0.000	0.923	0.152	0.000	0.001	0.734	0.850
SIT-AugT	0.684	0.362	0.000	-	0.583	0.825	0.002	0.000	0.856	0.452	0.010	0.002	0.543	0.262
SMT-JanT	0.000	0.009	0.561	0.583	-	0.008	0.178	0.368	0.258	0.068	0.080	0.009	0.768	0.632
SMT-FebT	0.024	0.000	0.097	0.825	0.008	-	0.142	0.702	0.272	0.000	0.028	0.033	0.970	0.490
SMT-JulyT	0.114	0.040	0.000	0.002	0.178	0.142	-	0.001	0.739	0.453	0.004	0.002	0.932	0.558
SMT-AugT	0.616	0.323	0.000	0.000	0.368	0.702	0.001	-	0.094	0.343	0.013	0.006	0.811	0.445
Bre-AugR	0.210	0.123	0.923	0.856	0.258	0.272	0.739	0.094	-	0.996	0.124	0.242	0.391	0.258
NAO-Feb	0.144	**0.000**	0.152	0.452	0.068	**0.000**	0.453	0.343	0.996	-	0.070	0.188	0.884	0.419
POINT-YR	0.104	0.035	0.000	0.010	0.080	0.028	0.004	0.013	0.124	0.070	-	0.000	0.401	0.910
BORAL-PN	**0.009**	**0.016**	**0.001**	**0.002**	**0.009**	**0.033**	**0.002**	**0.006**	0.242	0.188	**0.000**	-	0.245	0.155
OCEAN-PN	0.544	0.293	0.734	0.543	0.768	0.970	0.932	0.811	0.391	0.884	0.401	0.245	-	0.324
BORAL-BP	0.821	0.107	0.850	0.262	0.632	0.490	0.558	0.445	0.258	0.419	0.910	0.155	0.324	-
OCEAN-BP	0.248	0.667	0.576	0.165	0.434	0.692	0.441	0.504	0.253	0.935	0.958	**0.020**	**0.000**	0.841

Key **Bold** = statistically significant correlations

Pearson Correlation Results for: 1931-1980

Descriptive Statistics				
Variable	Mean	Std Dev.	Std Err	N
SIT-JanT	38.700	12.850	1.817	50
SIT-FebT	37.280	13.500	1.909	50
SIT-JulyT	124.960	7.559	1.069	50
SIT-AugT	126.380	8.111	1.147	50
SMT-JanT	20.740	16.090	2.275	50
SMT-FebT	22.400	16.977	2.401	50
SMT-JulyT	128.420	8.954	1.266	50
SMT-AugT	127.240	9.855	1.394	50
Bre-AugR	730.220	339.787	48.053	50
NAO-Feb	0.159	2.081	0.294	50
POINT-YR	99.000	27.646	3.910	50
BORAL-PN	98.460	20.420	2.888	50
OCEAN-PN	107.460	11.123	1.573	50
BORAL-BP	64.940	21.788	3.081	50
OCEAN-BP	71.600	18.066	2.555	50

Correlation Matrix (R)

	SIT-JanT	SIT-FebT	SIT-JulyT	SIT-AugT	SMT-JanT	SMT-FebT	SMT-JulyT	SMT-AugT	Bre-AugR	NAO-Feb	POINT-YR	BORAL-PN	OCEAN-PN	BORAL-BP
SIT-JanT	1.000	0.297	0.067	0.089	0.886	0.374	0.046	0.086	-0.078	0.133	0.284	0.227	0.231	-0.120
SIT-FebT	0.297	1.000	0.050	-0.101	0.357	0.927	0.023	-0.113	-0.001	0.577	0.288	0.273	0.332	0.010
SIT-JulyT	0.067	0.050	1.000	0.654	0.114	0.133	0.823	0.536	-0.319	0.000	0.034	0.192	0.422	-0.427
SIT-AugT	0.089	-0.101	0.654	1.000	0.195	-0.021	0.570	0.870	-0.481	0.001	0.034	0.140	0.289	-0.245
SMT-JanT	0.886	0.357	0.114	0.195	1.000	0.407	0.120	0.198	-0.116	0.138	0.334	0.196	0.329	-0.085
SMT-FebT	0.374	0.927	0.133	-0.021	0.407	1.000	0.116	-0.064	-0.010	0.710	0.294	0.307	0.407	-0.035
SMT-JulyT	0.046	0.023	0.823	0.570	0.120	0.116	1.000	0.563	-0.226	0.067	0.101	0.117	0.414	-0.207
SMT-AugT	0.086	-0.113	0.536	0.870	0.198	-0.064	0.563	1.000	-0.576	-0.055	0.166	0.182	0.334	-0.095
Bre-AugR	-0.078	-0.001	-0.319	-0.481	-0.116	-0.010	-0.226	-0.576	1.000	0.182	-0.203	-0.258	-0.295	0.047
NAO-Feb	0.133	**0.577**	0.000	0.001	0.138	**0.710**	0.067	-0.055	0.182	1.000	0.257	0.116	0.348	0.101
POINT-YR	0.284	0.288	0.034	0.034	0.334	0.294	0.101	0.166	-0.203	0.257	1.000	0.353	0.622	0.288
BORAL-PN	0.227	0.273	0.192	0.140	0.196	**0.307**	0.117	0.182	-0.258	0.116	**0.353**	1.000	0.284	-0.065
OCEAN-PN	0.231	**0.332**	**0.422**	**0.289**	**0.329**	**0.407**	**0.414**	**0.334**	**-0.295**	**0.348**	**0.622**	**0.284**	1.000	-0.079
BORAL-BP	-0.120	0.010	**-0.427**	-0.245	-0.085	-0.035	-0.207	-0.095	0.047	0.101	**0.288**	-0.065	-0.079	1.000
OCEAN-BP	0.035	0.132	0.108	0.034	0.079	0.191	0.063	-0.043	0.165	**0.348**	**0.304**	-0.015	**0.446**	-0.195

t Statistic

	SIT-JanT	SIT-FebT	SIT-JulyT	SIT-AugT	SMT-JanT	SMT-FebT	SMT-JulyT	SMT-AugT	Bre-AugR	NAO-Feb	POINT-YR	BORAL-PN	OCEAN-PN	BORAL-BP
SIT-JanT	-	2.154	0.466	0.622	13.233	2.798	0.317	0.595	0.544	0.929	2.048	1.613	1.648	0.836
SIT-FebT	2.154	-	0.349	0.704	2.649	17.092	0.162	0.787	0.005	4.892	2.082	1.964	2.437	0.066
SIT-JulyT	0.466	0.349	-	5.984	0.793	0.927	10.043	4.395	2.335	0.001	0.236	1.355	3.223	3.268
SIT-AugT	0.622	0.704	5.984	-	1.376	0.144	4.805	12.206	3.800	0.009	0.233	0.981	2.093	1.752
SMT-JanT	13.233	2.649	0.793	1.376	-	3.084	0.836	1.402	0.811	0.966	2.458	1.383	2.410	0.590
SMT-FebT	2.798	17.092	0.927	0.144	3.084	-	0.813	0.447	0.070	6.995	2.134	2.233	3.087	0.241
SMT-JulyT	0.317	0.162	10.043	4.805	0.836	0.813	-	4.722	1.604	0.468	0.701	0.818	3.147	1.467
SMT-AugT	0.595	0.787	4.395	12.206	1.402	0.447	4.722	-	4.884	0.382	1.164	1.281	2.454	0.660
Bre-AugR	0.544	0.005	2.335	3.800	0.811	0.070	1.604	4.884	-	1.284	1.434	1.853	2.136	0.323
NAO-Feb	0.929	**4.892**	0.001	0.009	0.966	**6.995**	0.468	0.382	1.284	-	1.842	0.811	2.572	0.702
POINT-YR	2.048	2.082	0.236	0.233	2.458	2.134	0.701	1.164	1.434	1.842	-	2.616	5.504	2.083
BORAL-PN	1.613	1.964	1.355	0.981	1.383	**2.233**	0.818	1.281	1.853	0.811	**2.616**	-	2.052	0.449
OCEAN-PN	1.648	**2.437**	**3.223**	**2.093**	**2.410**	**3.087**	**3.147**	**2.454**	**2.136**	**2.572**	**5.504**	**2.052**	-	0.546
BORAL-BP	0.836	0.066	**3.268**	1.752	0.590	0.241	1.467	0.660	0.323	0.702	**2.083**	0.449	0.546	-
OCEAN-BP	0.241	0.919	0.750	0.239	0.550	1.347	0.436	0.297	1.161	**2.571**	**2.208**	0.106	**3.453**	1.380

Correlation Significance (P)

	SIT-JanT	SIT-FebT	SIT-JulyT	SIT-AugT	SMT-JanT	SMT-FebT	SMT-JulyT	SMT-AugT	Bre-AugR	NAO-Feb	POINT-YR	BORAL-PN	OCEAN-PN	BORAL-BP
SIT-JanT	-	0.036	0.643	0.537	0.000	0.007	0.753	0.555	0.589	0.358	0.046	0.113	0.106	0.407
SIT-FebT	0.036	-	0.729	0.485	0.011	0.000	0.872	0.435	0.996	0.000	0.043	0.055	0.019	0.947
SIT-JulyT	0.643	0.729	-	0.000	0.432	0.359	0.000	0.000	0.024	0.999	0.815	0.182	0.002	0.002
SIT-AugT	0.537	0.485	0.000	-	0.175	0.886	0.000	0.000	0.000	0.993	0.817	0.331	0.042	0.086
SMT-JanT	0.000	0.011	0.432	0.175	-	0.003	0.407	0.167	0.421	0.339	0.018	0.173	0.020	0.558
SMT-FebT	0.007	0.000	0.359	0.886	0.003	-	0.420	0.657	0.945	0.000	0.038	0.030	0.003	0.811
SMT-JulyT	0.753	0.872	0.000	0.000	0.407	0.420	-	0.000	0.115	0.642	0.487	0.417	0.003	0.149
SMT-AugT	0.555	0.435	0.000	0.000	0.167	0.657	0.000	-	0.000	0.705	0.250	0.206	0.018	0.512
Bre-AugR	0.589	0.996	0.024	0.000	0.421	0.945	0.115	0.000	-	0.205	0.158	0.070	0.038	0.748
NAO-Feb	0.358	**0.000**	0.999	0.993	0.339	**0.000**	0.642	0.705	0.205	-	0.072	0.421	0.013	0.486
POINT-YR	0.046	0.043	0.815	0.817	0.018	0.038	0.487	0.250	0.158	0.072	-	0.012	0.000	0.043
BORAL-PN	0.113	0.055	0.182	0.331	0.173	**0.030**	0.417	0.206	0.070	0.421	**0.012**	-	0.046	0.656
OCEAN-PN	0.106	**0.019**	**0.002**	**0.042**	**0.020**	**0.003**	**0.003**	**0.018**	**0.038**	**0.013**	**0.000**	**0.046**	-	0.588
BORAL-BP	0.407	0.947	**0.002**	0.086	0.558	0.811	0.149	0.512	0.748	0.486	**0.043**	0.656	0.588	-
OCEAN-BP	0.811	0.363	0.457	0.812	0.585	0.184	0.665	0.767	0.251	**0.013**	**0.032**	0.916	**0.001**	0.174

Key **Bold** = statistically significant correlations

Change between 1881-1930 and 1931-1980 periods

Pearson Correlation Results for: 1881-1930

Descriptive Statistics				
Variable	Mean	Std Dev.	Std Err	N
SIT-JanT	40.660	11.587	1.639	50
SIT-FebT	37.760	11.909	1.684	50
SIT-JulyT	119.960	8.471	1.198	50
SIT-AugT	120.520	9.410	1.331	50
SMT-JanT	23.980	15.244	2.156	50
SMT-FebT	24.440	15.348	2.171	50
SMT-JulyT	123.600	9.187	1.299	50
SMT-AugT	121.260	9.245	1.307	50
Bre-AugR	878.080	383.417	54.223	50
NAO-Feb	0.999	2.077	0.294	50
POINT-YR	99.000	29.433	4.163	50
BORAL-PN	111.340	13.230	1.871	50
OCEAN-PN	161.420	36.083	5.103	50
BORAL-BP	58.760	14.264	2.017	50
OCEAN-BP	99.980	27.427	3.879	50

Pearson Correlation Results for: 1931-1980

Descriptive Statistics				
Variable	Mean	Std Dev.	Std Err	N
SIT-JanT	38.700	12.850	1.817	50
SIT-FebT	37.280	13.500	1.909	50
SIT-JulyT	124.960	7.559	1.069	50
SIT-AugT	126.380	8.111	1.147	50
SMT-JanT	20.740	16.090	2.275	50
SMT-FebT	22.400	16.977	2.401	50
SMT-JulyT	128.420	8.954	1.266	50
SMT-AugT	127.240	9.855	1.394	50
Bre-AugR	730.220	339.787	48.053	50
NAO-Feb	0.159	2.081	0.294	50
POINT-YR	99.000	27.646	3.910	50
BORAL-PN	98.460	20.420	2.888	50
OCEAN-PN	107.460	11.123	1.573	50
BORAL-BP	64.940	21.788	3.081	50
OCEAN-BP	71.600	18.066	2.555	50

Change	% decrease
-2.0	-5%
-0.5	-1%
5.0	4%
5.9	5%
-3.2	-14%
-2.0	-8%
4.8	4%
6.0	5%
-147.9	-17%
-0.8	-84%
0.0	0%
-12.9	-12%
-54.0	-33%
6.2	11%
-28.4	-28%