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Holocene fire in the Scottish Highlands: evidence from macroscopic charcoal records

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Abstract: It has been hypothesized that the mid-Holocene decline of pine (*Pinus sylvestris* L.) woodland in the Scottish Highlands may have been the result of a change in the fire regime of the region. Little is known about the Holocene fire history of these forests, although a number of factors suggest that fire may have played a significant role. This study examines whether fire was a prevalent factor in Scotland over the course of the Holocene and its relationship with Highland vegetation communities. Both macroscopic and microscopic charcoal are analysed in conjunction with a full palynological investigation from four Holocene lake sedimentary sequences in locations throughout the Scottish Highlands. Comparison of macroscopic charcoal abundance profiles with those from areas of known wildfire activity and the consistent pattern of burning revealed across the four disparate Highland sites indicate that broad-scale burning of vegetation did occur. Charcoal abundance was related to vegetation composition at all four of the sites examined. The abundance of pine, however, was found to be unrelated to fire history. Instead, fire appears to be predominantly linked to the development of heath and blanket mire communities. Analysis of three different macroscopic charcoal size fractions (≥ 500 μm, 250–500 μm and 125–250 μm) revealed strong correlations between measures. Microscopic charcoal abundance, however, was more variable and was determined to be a less accurate measure of local catchment-scale burning within the region.

Key words: Fire history, vegetation change, sedimentary charcoal, macroscopic charcoal, Scotland, *Pinus sylvestris*, Holocene.

Introduction

Much of the Scottish Highlands were covered by Scots pine (*Pinus sylvestris* L.) woodland during the Holocene, as is evidenced by both palynological evidence (Huntley and Birks, 1983; Birks, 1989) and the subfossil stumps preserved in peat throughout the region (Birks, 1975; Bennett, 2004a). Currently, only scattered fragments of this once vast postglacial pine forest remain (Steven and Carlisle, 1959; Forestry Authority, 1994). Various hypotheses have been proposed to explain what appears to have been a dramatic, regional decline of the species throughout Scotland around 4400 cal. BP (cf. Bennett, 1995). 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. Evidence of the increased growth of mire-rooting pine trees following fire at sites in England, Wales and southwest Ireland (Lageard *et al.*, 2000) further supports the hypothesized fire-dependency of the species within the British Isles.

Although the wet climate and predominantly non-forest vegetation of the Scottish Highlands today does not intuitively suggest the importance of fire as a dominant ecological process, several factors indicate that fire may have played a significant role in Scottish pine forests throughout the Holocene. First, *Pinus sylvestris* is the only native tree species in the British Isles that is easily combustible (Rackham, 1986) and fires have been reported to occur within present-day pine stands in the Highlands (Steven and Carlisle, 1959; Anonymous, 1970; Farmer, 1979). Second, in coniferous forest regions of the world under similar climatic conditions, such as the Pacific Northwest of North America, fire is the predominant landscape pattern-forming disturbance process (Franklin and Dyrness, 1973; Agee, 1993; Weisberg and Swanson, 2003). Finally, throughout the distribution of the

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genus, *Pinus* commonly forms fire-dependent communities (Agee, 1998).

It has long been speculated that natural fire may have helped shape Scottish pinewood communities (Durno and McVean, 1959; McVean, 1963; Rackham, 1986). The nature of this proposed past fire regime, whether it may have been one of infrequent, catastrophic fires such as occurs in the coastal temperate rainforests of North America or of frequent, low intensity fires such as is common in pine communities of more continental climatic regions (Franklin and Dyrness 1973; Zackrisson 1977; Agee 1993; Pitkänen 2000), is completely unknown. Little in general is known about the Holocene fire history of Scottish pine forests or even whether widespread, landscape-level burning of vegetation ever occurred. The existence of the hypothesized relationship between pine and fire could be revealed in the charcoal records from lake sediments in the Highlands in three ways. First, if fire was necessary for the creation of a suitable seedbed for pine regeneration then elevated charcoal levels should immediately precede the establishment of pine populations at a site. Second, if fire was required for perpetuating the conditions suitable for the maintenance of pine dominance, such as through the exclusion of competitors, then elevated charcoal levels should directly coincide with past periods of abundant pine populations revealed within the palynological record. Finally, if it was a change in fire regime that caused Scottish pine populations to decline during the mid-Holocene then there should be a dramatic shift in charcoal abundance at sites exhibiting evidence of a 'pine decline'.

Detailed, quantitative assessments of charcoal abundance within Scottish Holocene sedimentary sequences are scarce and existing data suffer both methodological and interpretative difficulties (Tipping, 1996), making comparison among sites problematic. The bulk of the existing evidence may be broadly divided into two categories. First, are detailed, quantitative assessments of microscopic charcoal abundance from more recently examined sites in the Inner Hebrides (Robinson and Dickson, 1988) and the Western (Bohncke, 1988; Fossitt, 1990; Bennett *et al.*, 1990; Edwards *et al.*, 1995) and Northern Isles (Bennett *et al.*, 1992, 1993; Edwards and Moss, 1993; Bunting, 1994), which are predominantly outside the Holocene range of pine dominance. Second, are coarse-resolution assessments of macroscopic charcoal within sequences from the Scottish mainland, often described either as part of lithostratigraphic or plant macrofossil analyses (Durno and McVean, 1959; Birks, 1972, 1975). Regional syntheses for Scotland (Edwards, 1990, 1996; Tipping, 1996) have been based primarily on the microscopic charcoal evidence, from sites largely beyond the range of *Pinus sylvestris*, and have focused predominantly on the charcoal record as an indicator of Mesolithic human activity. A few recent investigations (Smith, 1996; Davies, 1999) provide more detailed charcoal profiles for mainland sites, but these have not been included in regional syntheses.

Methodical, quantitative charcoal assessments from sites throughout the Holocene range of pine are necessary to examine the relationship between fire and pinewood communities. The adoption of a common methodology is vital to facilitate comparison both amongst Scottish sites and to compare results with areas of known landscape-level wildfire occurrence. Charcoal studies in the past have suffered from lack of standardization of techniques and analytical assumptions (Whitlock and Larsen, 2001). Much of the quantitative charcoal evidence that exists in Scotland is based on the examination of microscopic charcoal fragments that can be transported over long distances (Chandler *et al.*, 1983; Clark, 1988a). It is therefore unknown what proportion of the charcoal input at an individual site is derived from regional sources and how much from more localized burning. In contrast, larger macroscopic charcoal fragments have a localized input (Patterson *et al.*, 1987; Clark, 1988a; Whitlock and Millspaugh, 1996; Whitlock and Larsen, 2001) and, therefore, provide a more direct assessment of the relationship between fire and vegetation change. Discrepancies exist in the literature as to correspondence amongst these different charcoal fractions and their efficacy in measuring fire events (Swain, 1973, 1978; Patterson *et al.*, 1987; Clark, 1988b, 1990; MacDonald *et al.*, 1991; Millspaugh and Whitlock, 1995; Whitlock and Millspaugh, 1996). Most studies suggest, however, that the predominance of macroscopic charcoal ($> 100\ \mu m$) is not transported far from the source of a fire (Whitlock and Larsen, 2001). Ohlson and Tryterud (2000) found that virtually no particles $> 500\ \mu m$ were deposited beyond the immediate vicinity of the fire margins following burning of forested sites in Boreal Scandinavia. Wein *et al.* (1987) report that macroscopic charcoal particles $> 200\ \mu m$ can be transported up to 500 m, while Whitlock and Millspaugh (1996) indicate that most particles $> 125\ \mu m$ are deposited within 7 km of a fire source. While precise source area estimates may vary between studies, the evidence strongly suggests that the predominance of macroscopic charcoal deposition occurs within the local watershed.

The primary goal of this study is to examine the relationship between localized burning and patterns of vegetation change over time in the Highlands. Macroscopic charcoal analysis was combined with the analysis of fossil pollen from sites with well-defined local catchments throughout the Scottish Highlands (Figure 1) in order to determine:

Figure 1 Location map of the four sites analysed in this study

(1) if landscape-level burning of vegetation has been prevalent throughout the Holocene or if the Scottish charcoal record is simply the result of anthropogenic, domestic-scale fires;
(2) the relationship between fire and long-term vegetation composition, and specifically whether Holocene pine communities in the Highlands were fire-dependent;
(3) the most accurate and expedient methodology for future fire history assessments in the region.

Three different macroscopic charcoal size fractions, as well as microscopic charcoal abundance, were examined using standardized methods (Whitlock and Larsen, 2001) to assess the degree of correspondence between measures at sites in Scotland and to facilitate the development of a common methodology for future investigations. The goal of this analysis was to determine initially whether fire was ever a significant disturbance factor in the Highlands during the Holocene and, if it was, to examine the relationship between fire and vegetation change, particularly the presence of *Pinus sylvestris*. The intent is not to identify individual fire events or to calculate fire return intervals at the sites examined. Such analyses would require both a strategy of contiguous sampling resolution and also ideally, calibration with known fire events to test the reliability of the various charcoal measures and to determine the 'background' charcoal levels within an area (Whitlock and Larsen, 2001). This level of detail is not possible in the Highlands. Even within areas of known and measurable recent fires, these types of analyses have revealed conflicting results as to which charcoal measures effectively correspond to known local fire events (MacDonald *et al.*, 1991; Millspaugh and Whitlock, 1995). The level of detail necessary for identifying individual fire events is not the aim of the current study, but will remain a topic for future analyses.

Methods

Sample collection

Four Holocene lake sedimentary sequences from the Scottish Highlands (UK) were analysed for fossil pollen, microscopic and macroscopic charcoal: Loch an Amair in the Glen Affric Forest Reserve, Dubh-Lochan in the Great Glen, Lochan na h-Inghinn on the northwest coast and Reidh-lochan in eastern Sutherland (Figure 1). Relatively small lakes, 100–200 m diameter and 2.0–5.0 m depth (Table 1), with well-defined, rocky shorelines and no inflowing streams, were selected for analysis in order to provide continuous, undisturbed sedimentary sequences (cf. Bennett *et al.*, 1992) to which the pollen and charcoal input is predominantly received from the surrounding catchment (Jacobson and Bradshaw, 1981; Clark, 1988a, 1990; Millspaugh and Whitlock, 1995; Whitlock and Larsen, 2001).

Sediment cores were collected using a modified 5 cm diameter Livingstone piston corer (Wright, 1967) from an inflatable dinghy secured in the centre of each lake. The 1 m long core segments were extruded from the corer in the field, wrapped in plastic film, aluminium foil and thick plastic, and stored in the dark at 4°C prior to subsampling. The total length and description of the sediment sequence at each site is presented in Table 1, sediment depths are measured from the lake surface. A basal layer of grey clay was reached at Loch an Amair, Dubh-Lochan and Lochan na h-Inghinn, indicative of lateglacial sediments. At Reidh-lochan a layer of gravel was reached 1070 cm from the lake surface and the sediments could not be cored any deeper. Two series of overlapping cores approximately 1 m apart were taken from each site, one at even-metre intervals, the other on the half-metre. A single consecutive series encompassing the sediment–water interface was analysed at Loch an Amair, Dubh-Lochan and Lochan na h-Inghinn. As a result of a 30 cm gap in the half-metre series at

Table 1 Site descriptions. Characteristics of the sampled lakes, sediments and surrounding catchments

	Loch an Amair	Dubh-Lochan	Lochan na h-Inghinn	Reidh-lochan
Location	NH 264 261; 4°53′25″W 57°17′20″N	NH 531 246; 4°26′7″W 57°17′26″N	NC 189 334; 5°05′30″W 58°15′15″N	NC 742 071; 4°07′26″W 58°02′13″N
Elevation	315 m	150 m	65 m	160 m
Lake diameter	100 m	125 m	110 m	100 m
Lake depth	3.25 m	3.50 m	3.14 m	4.57 m
Sediment core length	3.18 m	6.18 m	5.70 m	6.13 m
Sediment description (depth cm)	325–514 Detritus gyttja 514–641 Gyttja 641–643 Clay/gravel	350–396 Detritus gyttja 396–450 Gyttja 450–650 Detritus gyttja 650–965 Gyttja 965–967 Gyttja/gravel 967–967.5 Clay w/sand	314–400 Silty gyttja 400–840 Gyttja 840–880 Detritus gyttja 880–881 Clay 881–884 Clay w/gravel	457–1069 Gyttja
Catchment geology and soils	Metamorphosed sedimentary rocks of the Moine succession. Soils are peaty podzols and humus-iron podzols	Conglomerate Middle Old Red Sandstone, with intrusive igneous rock in SE. Soils are a mix of peaty and podzolic rankers and humus-iron podzols	Precambrian Lewisian gneiss. 'Knock-and-lochan' topography (Linton, 1963). Peaty rankers and peaty gleys on knolls, interspersed with deep peat	Acid, coarse-grained intrusive igneous rock. Soils include deep peat, and peaty and humus-iron podzols
Catchment vegetation	Non-native *Pinus contorta* plantations, with *Pinus sylvestris* woodland on the northern slopes	*Betula* woodland. Open, grazed areas bordering the lake are dominated by Poaceae, *Calluna vulgaris* and *Sphagnum*	*Betula* woodland on W and SW hillslopes, remainder of the catchment covered by blanket mire	Blanket mire. Agricultural development in the eastern section

Location is denoted by British National Grid Reference, latitude and longitude. Elevation is metres above mean sea level. Sediment depths are measured from the lake surface. Lithostratigraphy follows the Troels-Smith classification system (Troels-Smith, 1955), more detailed diagrammatic descriptions are shown in Figures 2–5. The Reidh-lochan sequence includes the upper 43 cm of the overlapping sediment core.

Reidh-lochan the even-metre sequence, which did not include the uppermost sediments, was analysed, supplementing the sequence with the upper 43 cm of the overlapping core. Lithostratigraphic features of the sediments were described using the Troels-Smith (1955) classification system (Table 1). Subsamples were taken at 8 cm intervals in the Lochan na h-Inghinn, Dubh-Lochan and Reidh-lochan sequences and at 4 cm intervals at Loch an Amair using a modified syringe (2.5 cm^3) for macroscopic charcoal analysis and a brass sampler (0.5 cm^3) for pollen and microscopic charcoal analyses. Samples were preserved in a mixture of formalin and alcohol before processing.

Dating

Six bulk-sediment samples from each site (Table 2) were radiometrically dated using liquid scintillation counting at the NERC Radiocarbon Laboratory in East Kilbride, Scotland (Harkness and Wilson, 1972). An additional recheck sample was analysed for Loch an Amair as a result of similarity between two of the sample ages. Samples were pretreated by digestion in 1 M HCl at 80°C for 24 hours, washed free of acid, filtered and oven dried to a constant weight. Conventional ^{14}C ages BP (AD 1950) are reported at the 1σ level for overall analytical confidence following the established international practice for calculation of radiocarbon ages (Stuiver and Polach, 1977). Radiocarbon ages were converted to calendar ages (cal. yr BP) using the calibration program CALIB (4.3) (Stuiver and Reimer, 1993) and the INTCAL98 calibration data set (Stuiver *et al.*, 1998), with a laboratory error multiplier of 1.2. Calendar age ranges are calculated at the 2σ level, using the probability distribution method (Stuiver and Reimer, 1993). Median calendar ages and standard deviations for age–depth modelling were determined based on a 95% minimum probability of occurrence. A number of age–depth models were fitted to the calibrated ages at each site. Final models were selected (Table 2) based on calculated 'goodness-of-fit' (Bennett, 1994) and the determination of realistic transitions in sedimentation rates. Sediment depth and age scales at each site are shown in Figures 2–5.

Charcoal

Microscopic charcoal particles were counted on the pollen analysis microscope slides using the point count estimation method of Clark (1982). For each slide, 50 fields of view were examined, with 202 counting points in each field of view. Macroscopic charcoal analysis generally follows the methodology of Millspaugh and Whitlock (1995). The sediments at Loch an Amair, Dubh-Lochan and Reidh-lochan were not flocculated and required no pretreatment. The Lochan na h-Inghinn samples were soaked in a solution of 10% sodium hexametaphopsphate for two days to deflocculate the sediment. The samples were washed to remove the formalin and alcohol preservation mixture before soaking. All samples were gently washed, using a shower head attachment and a small sable paint brush, through a set of nested sedimentology sieves, with mesh sizes of 500 μm, 250 μm and 125 μm. The sieved samples were washed into gridded petri dishes and charcoal particles were tallied under a ×40 magnification stereomicroscope. Identification of charcoal fragments was based on colour, shape and surface structure of the fragment, reflectivity under a fibre optic light source, and nature of the fragment when crushed with a dissecting needle

Table 2 Age determinations

Site	Laboratory code	Depth (cm)	Conventional ^{14}C age (BP)	Calendar age (cal. BP)	Age–depth model
Loch an Amair	SRR-6262	348–354	1240±45	1170±115	4-term polynomial
	SRR-6263	380–386	1205±45	1125±140	$(y = 42.50 + 21.26x +$
	SRR-6312	410–416	2555±50	2615±160	$0.126x^2 - 0.0003x^3)$
	SRR-6264	454–461	4020±40	4515±110	
	SRR-6265	514–521	5940±50	6770±135	
	SRR-6266	554–562	7690±50	8485±100	
	SRR-6267	632–640	9400±50	10 740±315	
Dubh-Lochan	SRR-6576	390–395	2075±50	2020±135	Linear interpolation
	SRR-6577	597–603	3550±50	3835±150	
	SRR-6578	736–742	6800±50	7655±90	
	SRR-6579	793–799	8105±55	9020±250	
	SRR-6580	915–920	9330±55	10 480±210	
	SRR-6581	957–963	9715±55	11 000±240	
Lochan na h-Inghinn	SRR-6256	390–397	855±45	795±120	5-term polynomial
	SRR-6257	531–538	2765±45	2865±105	$(y = 3.61 + 4.97x +$
	SRR-6258	578–585	3660±40	3965±125	$0.079x^2 - 0.0002x^3 +$
	SRR-6259	718–727	6055±50	6880±145	$2.86e^{-07}x^4)$
	SRR-6260	820–827	9360±55	10 560±180	
	SRR-6261	869–877	12 020±100	14 240±610	
Reidh-lochan	SRR-6582	509–514	1280±55	1180±120	6-term polynomial
	SRR-6583	666–675	2620±50	2675±190	$(y = 1.32 + 30.31x -$
	SRR-6584	787–793	3530±50	3810±170	$0.197x^2 + 0.0009x^3 -$
	SRR-6585	927–933	3940±55	4350±180	$1.81e^{-06}x^4 + 1.39e^{-09}x^5)$
	SRR-6586	1010–1020	5475±55	6260±150	
	SRR-6587	1060–1068	7900±55	8790±200	

Radiocarbon dates are reported as conventional radiocarbon years BP (AD 1950) and calculated at the 1σ level for analytical confidence. Calendar age determinations are based on the INTCAL98 calibration data set (Stuiver *et al.*, 1998), calculated at the 2σ level using the probability distribution method, CALIB 4.3 (Stuiver and Reimer, 1993). Median calendar ages and standard deviations were determined based on a 95% minimum probability of occurrence. Calibrated ages and standard deviations are rounded to the nearest 5-yr interval, or to the nearest decade when the ^{14}C age standard deviation > 50 years. Sample depths are measured from the lake surface.

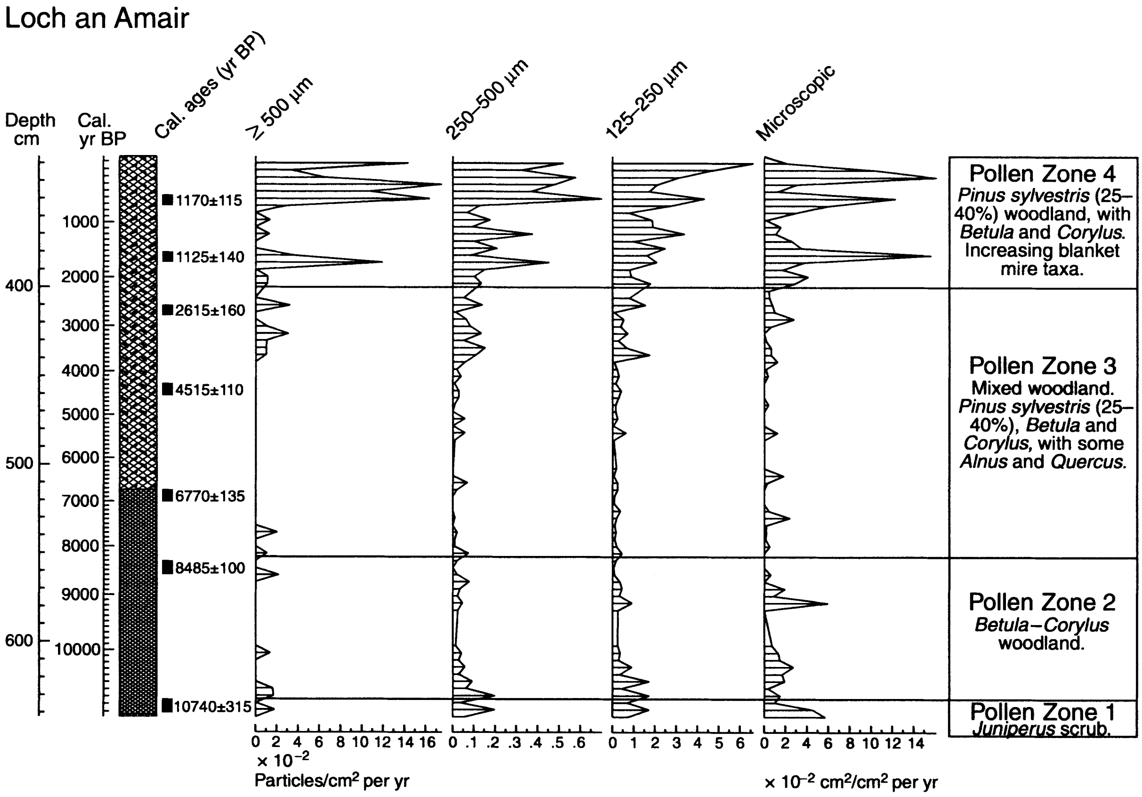

Figure 2 Variation in accumulation rates of microscopic and three macroscopic charcoal size fractions (≥ 500 µm, 250–500 µm and 125–250 µm) from Loch an Amair plotted against sediment depth (cm). Timescale (cal. BP), Troels-Smith (1955) lithostratigraphic classification and calibrated radiocarbon sample ages (Table 2) are shown on the left. The pollen assemblage zones derived from the pollen and spore frequency analysis are indicated by horizontal lines and a summary of the predominant vegetation within each zone is displayed in labelled boxes on the right

(Whitlock and Larsen, 2001).The total number of charcoal pieces was tallied in the following size classes: ≥ 500 µm, 250–500 µm and 125–250 µm. Charcoal accumulation rates were determined based on the modelled sediment accumulation rates and the charcoal concentrations.

Pollen

Extraction of the fossil pollen from the sedimentary material follows the processing methodology described by Bennett and Willis (2001). A known concentration of exotic *Eucalyptus* pollen in a glycerol suspension was first added to each sample for the determination of pollen and microscopic charcoal concentrations (Benninghoff, 1962). Sediments were treated with hydrochloric acid to remove carbonates, and hot NaOH followed by coarse sieving at 180 µm to remove humic acids and bulk material. Treatment with hydrofluoric acid was used to remove silica and silicates, and acetolysis was used for the removal of polysaccharides. The remaining residues were stained with 0.2% aqueous safranin and mounted in silicone oil (see Bennett and Willis, 2001, for detailed methodology).

Pollen and spores were tallied using a transmitted light microscope at × 400 magnification, scanning slides along regularly spaced traverses. A minimum of 500 identifiable pollen grains and spores of vascular plants, excluding obligate aquatics and exotic pollen markers, were counted at each sampling level and frequencies are presented as a proportion of this total land pollen and spore sum (ΣTLP). Frequencies of excluded types were calculated as a proportion of their own sum added to ΣTLP. Pollen and spores were identified using the reference collection in the Department of Plant Sciences, University of Cambridge. Palynological nomenclature follows Bennett (2004b). Numerical zonation analysis, stratigraphically dividing each sequence into statistically significant pollen assemblage zones (Bennett, 1996), was conducted including all pollen and spore taxa with a minimum 5% frequency of occurrence (Birks and Berglund, 1979). The ANSI C program Psimpoll (4.00) (Bennett, 2004c) was used for the numerical handling and diagrammatic presentation of results.

Results

Charcoal accumulation rates

Accumulation rates of both microscopic and macroscopic charcoal at the four sites are displayed in Figures 2–5. Microscopic charcoal was assessed during the pollen counts and is reported as the area of microscopic charcoal accumulated per unit area of sediment per year (cm^2/cm^2 per yr). Raw counts of macroscopic charcoal particles in the three size classes, ≥ 500 µm, 250–500 µm and 125–250 µm, were converted to accumulation rates of the total number of particles per unit area of sediment per year (particles/cm^2 per yr). Maximum raw counts found at each site by decreasing size fraction are: Loch an Amair (11, 47, 369 particles), Dubh-Lochan (5, 56, 381), Lochan na h-Inghinn (6, 28, 341) and Reidh-lochan (1, 8, 57). The pattern of accumulation over time was revealed to be generally similar across all four of the charcoal measures evaluated, although the results are more variable at Reidh-lochan (Figure 5).

Charcoal accumulation rates at Loch an Amair (Figure 2) are slightly elevated in the early Holocene, decreasing after 8600 cal. BP. There is little charcoal present at the site throughout the mid-Holocene, but it steadily increases after 3800 cal. BP. The highest macroscopic charcoal levels occur

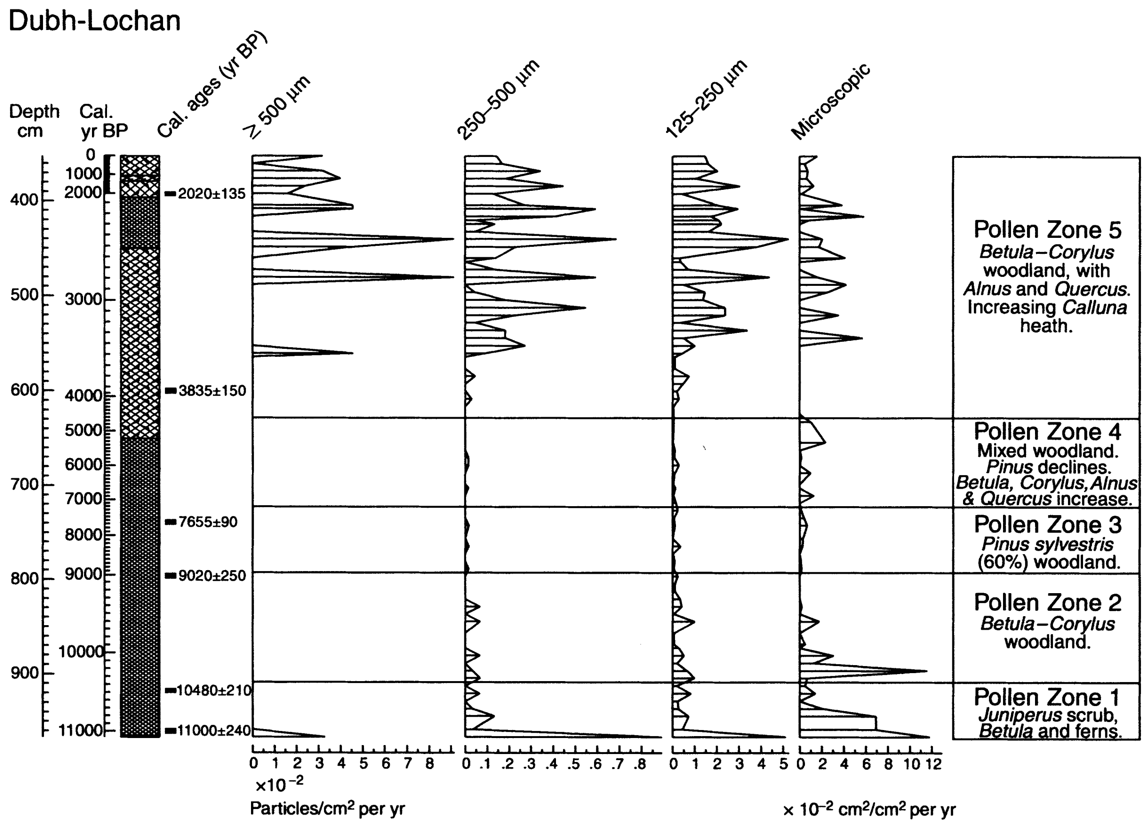

Figure 3 Variation in accumulation rates of microscopic and three macroscopic charcoal size fractions (≥ 500 µm, 250–500 µm and 125–250 µm) from Dubh-Lochan plotted against sediment depth (cm). Timescale (cal. BP), Troels-Smith (1955) lithostratigraphic classification, and calibrated radiocarbon sample ages (Table 2) are shown on the left. The pollen assemblage zones derived from the pollen and spore frequency analysis are indicated by horizontal lines and a summary of the predominant vegetation within each zone is displayed in labelled boxes on the right

after 700 cal. BP. Compared with the other three sites examined in this study, charcoal levels at Loch an Amair are moderate. The site does, however, have the highest accumulation rates in the ≥ 500 µm size fraction.

Elevated levels of all size fractions occur in the basal sample of the Dubh-Lochan (Figure 3) sequence, at 11 070 cal. BP. There is continued presence of microscopic and the smaller (250–500 µm and 125–250 µm) macroscopic size fractions until around 9600 cal. BP. Little charcoal is present throughout the mid-Holocene. Sustained higher charcoal accumulation rates occur in the upper portion of the sequence, beginning around 3500 cal. BP. Charcoal levels at Dubh-Lochan are moderate in comparison with the other sites, with mid-range values in all size fractions.

No charcoal occurs in the lateglacial portion of the Lochan na h-Inghinn (Figure 4) sequence, but it appears early in the Holocene and remains in moderate abundance until around 6500 cal. BP when it drops to minimal levels. There is a significant increase in charcoal after 500 cal. BP. Lochan na h-Inghinn reveals the highest maximum accumulation rates of the four sites examined for microscopic and the 250–500 µm and 125–250 µm charcoal size fractions.

Macroscopic charcoal particles ≥ 500 µm, the largest measured size fraction, are infrequent at Reidh-lochan (Figure 5) with only two occurrences. The Reidh-lochan profile does not encompass the early Holocene, beginning around 8800 cal. BP, and there is little charcoal in the lower portion of the sequence. There is a steady increase of charcoal in the 125–250 µm size fraction beginning around 4800 cal. BP. Charcoal levels in both the 125–250 µm and 250–500 µm size classes are highest between approximately 3900 and 2800 cal. BP. Macroscopic charcoal levels decrease after this time, but microscopic levels remain high. Macroscopic charcoal accumulation rates at Reidh-lochan are low in comparison with the other sites analysed, but microscopic charcoal accumulation is similar to rates found at both Loch an Amair and Dubh-Lochan.

Charcoal size fractions

Correlation analysis was performed on charcoal abundance, ie, the total number of particles per cm^3 of sediment for the three macroscopic fractions and the total area (cm^2) of microscopic charcoal per cm^3 of sediment, to examine the relationship between charcoal measures. All three macroscopic charcoal size fractions were found to be significantly correlated ($P < 0.001$) at Loch an Amair, Dubh-Lochan and Lochan na h-Inghinn (Table 3), with r-values between 0.550 and 0.958. Microscopic charcoal results were more variable. Microscopic charcoal abundance was significantly correlated (at the $P \leq 0.05$ level) with all three macroscopic measures at both Loch an Amair and Dubh-Lochan (r-values ranged from 0.255 to 0.517). At Lochan na h-Inghinn, however, only the 250–500 µm class was found to be weakly correlated ($r = 0.259$, $P \leq 0.05$) with microscopic charcoal levels. In the Reidh-lochan sequence, where there was minimal presence of charcoal particles ≥ 500 µm, only the smaller macroscopic fractions (125–250 µm and 250–500 µm) were significantly correlated ($r = 0.505$, $P < 0.001$). Microscopic charcoal abundance was not correlated with macroscopic charcoal at Reidh-lochan.

Charcoal and vegetation change

Charcoal abundance by pollen assemblage zone was examined in order to assess the relationship between charcoal and

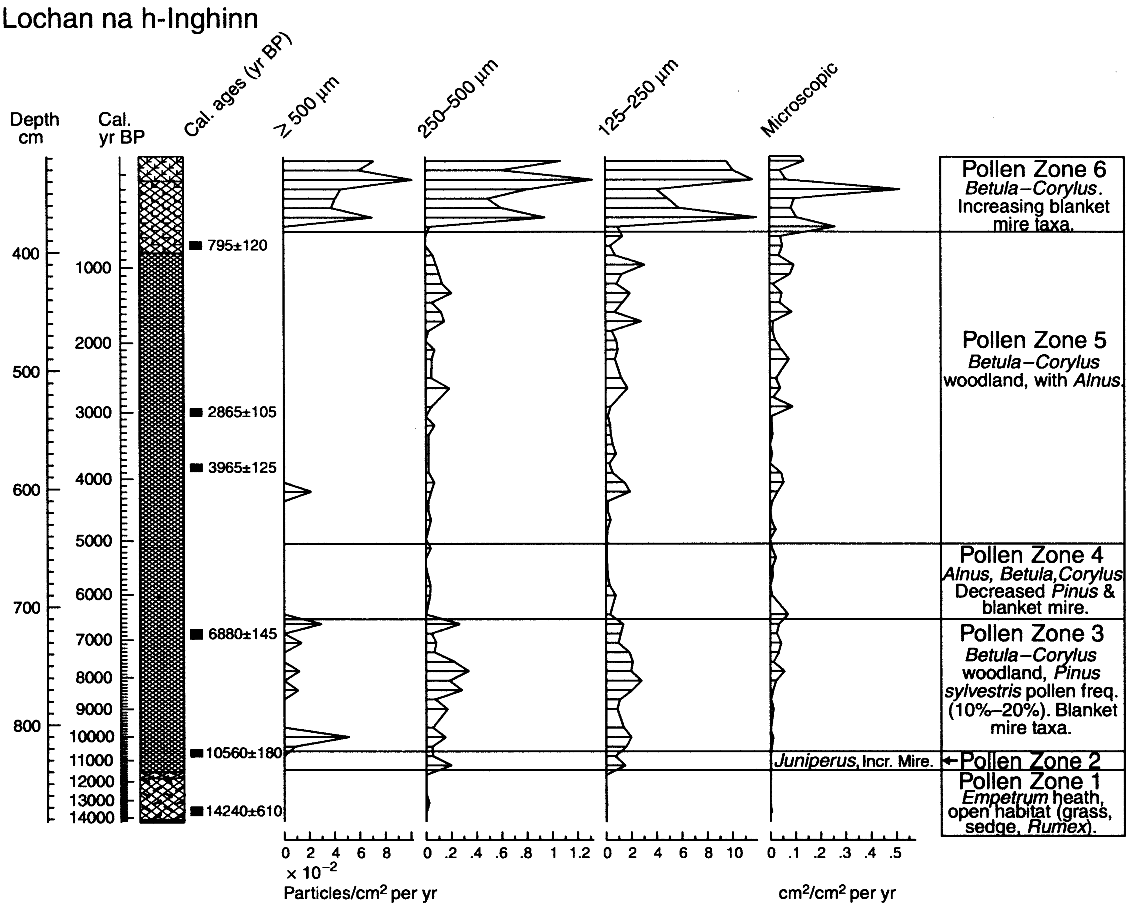

Figure 4 Variation in accumulation rates of microscopic and three macroscopic charcoal size fractions (≥ 500 µm, 250–500 µm and 125–250 µm) from Lochan na h-Inghinn plotted against sediment depth (cm). Timescale (cal. BP), Troels-Smith (1955) lithostratigraphic classification, and calibrated radiocarbon sample ages (Table 2) are shown on the left. The pollen assemblage zones derived from the pollen and spore frequency analysis are indicated by horizontal lines and a summary of the predominant vegetation within each zone is displayed in labelled boxes on the right

vegetation change at each site. The pollen assemblage zones and summary of the predominant vegetation changes resulting from a full palynological investigation (Froyd, 2002) are displayed on the charcoal accumulation profiles (Figures 2–5). Zonations were determined independently from the charcoal results. One-way ANOVA analysis was used to compare mean charcoal values of the four size fractions among pollen assemblage zones at each site (Table 4). All four charcoal size fractions were found to be significantly related to the pollen assemblage zones at Loch an Amair ($P \leq 0.01$), Dubh-Lochan ($P \leq 0.05$) and Lochan na h-Inghinn ($P \leq 0.01$). Only the smaller macroscopic charcoal size fractions were found to be significantly ($P \leq 0.01$) different among pollen assemblage zones at Reidh-lochan, where no significant relationship was found for microscopic charcoal or for the uncommon ≥ 500 µm fraction. A possible concern for the use of ANOVA in this analysis is the inequality of sample sizes between zones, particularly the lowermost zones at Loch an Amair and Lochan na h-Inghinn. The analysis was re-run omitting these samples and results were similar.

Mean charcoal abundance among pollen assemblage zones was compared using Fisher's Least Significance Difference (LSD) test (see Froyd, 2002). Results reveal that charcoal abundance is significantly higher in the uppermost zone pollen assemblage zone at Loch an Amair ($P \leq 0.01$), Dubh-Lochan ($P \leq 0.05$) and Lochan na h-Inghinn ($P \leq 0.01$). Additionally, charcoal levels during the early Holocene (Pollen Zones 2 and 3) at Lochan na h-Inghinn (Figure 4) were also found to be significantly elevated. In contrast, the only statistically significant relationship revealed at Reidh-lochan was elevated macroscopic charcoal levels throughout Pollen Zone 3, from 3980 to 1970 cal. BP.

Correlation analysis was performed between the charcoal measures and pollen concentrations (Odgaard, 1994) of *Pinus sylvestris* and *Calluna vulgaris* at each site (Table 5) to assess both the relationship between charcoal and pine abundance, and also to examine a possible correspondence between charcoal and heathland/mire development that was observed in the palynological investigation. Charcoal levels are generally not correlated with pine pollen abundance. The only significant correlations are between *Pinus sylvestris* pollen concentrations and charcoal 250–500 µm at Lochan na h-Inghinn, and with microscopic charcoal at Reidh-lochan. In contrast, charcoal was found to be strongly positively correlated with abundance of *Calluna vulgaris* at all four of the sites examined.

Discussion

Charcoal is present throughout the Holocene at all four of the sites examined in this study (Figures 2–5), with well-defined periods of increased abundance. The consistency seen in abundance patterns between charcoal fragments ≥ 500 µm and the other charcoal size fractions is indicative of the local

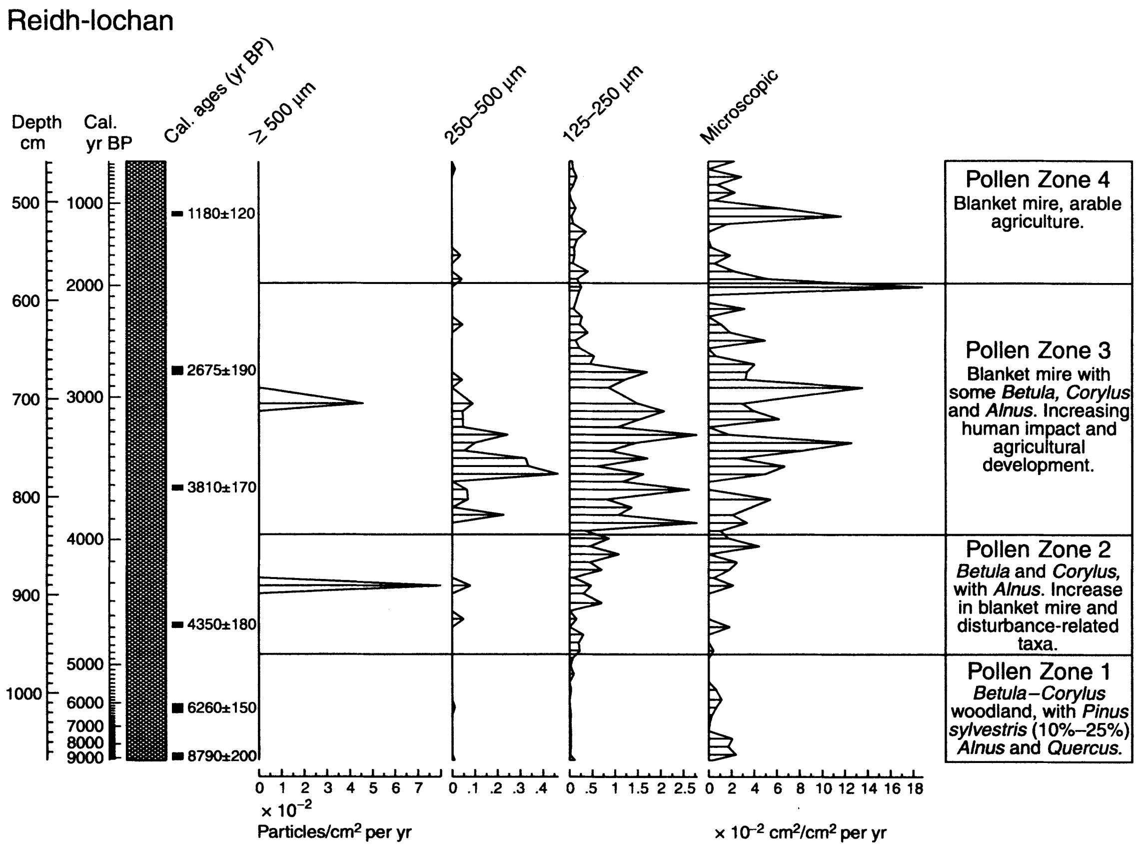

Figure 5 Variation in accumulation rates of microscopic and three macroscopic charcoal size fractions (≥ 500 µm, 250–500 µm and 125–250 µm) from Reidh-lochan plotted against sediment depth (cm). Timescale (cal. BP), Troels-Smith (1955) lithostratigraphic classification, and calibrated radiocarbon sample ages (Table 2) are shown on the left. The pollen assemblage zones derived from the pollen and spore frequency analysis are indicated by horizontal lines and a summary of the predominant vegetation within each zone is displayed in labelled boxes on the right

presence of fire within the catchments, because fragments of this size are not easily transported (Clark, 1988a; Clark and Patterson, 1997; Ohlson and Tryterud, 2000). But are the charcoal levels encountered indicative of landscape-level burning of vegetation or are they the result of something else, for example, local domestic fires?

Many compounding factors affect charcoal deposition to a lake system including atmospheric transport processes, fire behaviour, site topography, vegetation characteristics and sedimentological processes functioning within the lake itself (Whitlock and Larsen, 2001). Charcoal accumulation rates are, therefore, not directly comparable between sites. Because the history of burning in the Scottish pinewoods is largely unknown, sedimentary charcoal levels cannot be calibrated by comparison with known wildfire events. As a result, a rough comparison of accumulation rates with studies using similar methodologies in areas of known fire activity was used to make an initial determination of whether landscape-level fire appears to have even been a possibility within the region. Charcoal accumulation rate peaks are of a similar order of magnitude to those reported in lake sedimentary sequences from sites with known histories of wildfire in coniferous forests of western North America (Table 6). Although the comparison of absolute charcoal accumulation rates between sites is problematic, the order of magnitude of macroscopic charcoal levels revealed in this study is indeed consistent with landscape-level burning of vegetation and large-scale fire cannot be excluded as having played a significant role in the Highlands throughout the course of the Holocene.

Direct comparison of accumulation rates with recent macroscopic charcoal studies in other regions that would be of interest, particularly coniferous forest areas in Scandinavia, is often problematic because of differences in methodologies and types of sites examined. Both Ohlson and Tryterud (1999) and Lindbladh *et al.* (2003) report much higher (100×) concentrations of charcoal ≥ 500 µm within Scandinavian peat sequences than those found in the Scottish lakes. Conversely, Bradshaw and Hannon (1992) found charcoal accumulation levels of a similar order of magnitude to those revealed by this study in a southern Swedish peat sequence.

In addition to levels of macroscopic charcoal abundance, other factors indicate that the Highland charcoal records are derived from the landscape-level burning of vegetation rather than from domestic fires. These are four disparate sites, with very different environmental and anthropogenic histories (Froyd, 2002), yet they reveal some broad-scale consistent patterns of burning. Loch an Amair has been constantly forested by *Pinus sylvestris* throughout much of the Holocene. Both Dubh-Lochan and Lochan na h-Inghinn have also largely remained forested, with *Betula–Corylus* woodland at Lochan na h-Inghinn and Dubh-Lochan supporting an early to mid-Holocene pine forest, which was replaced by a mixed woodland. Contrastingly, mire communities have predominated at Reidh-lochan for the last 4000 years. Anthropogenic disturbance is much more prevalent at Reidh-lochan than at the other sites, with evidence of arable agriculture beginning as early as 4820 cal. BP. Evidence of human impact is low at both Loch an Amair and Lochan na h-Inghinn, while the first indication of human impact at Dubh-Lochan in the Great

Table 3 Correlations between charcoal size fractions

			250–500 μm	125–250 μm	Microscopic
Loch an Amair	≥ 500 μm	*r*	0.840	0.622	0.392
		P-value	< 0.001**	< 0.001**	0.001**
	250–500 μm	*r*		0.827	0.485
		P-value		< 0.001**	< 0.001**
	125–250 μm	*r*			0.517
		P-value			< 0.001**
Dubh-Lochan	≥ 500 μm	*r*	0.775	0.746	0.255
		P-value	< 0.001**	< 0.001**	0.034*
	250–500 μm	*r*		0.958	0.374
		P-value		< 0.001**	0.002**
	125–250 μm	*r*			0.367
		P-value			0.002**
Lochan na h-Inghinn	≥ 500 μm	*r*	0.550	0.579	0.148
		P-value	< 0.001**	< 0.001**	0.238
	250–500 μm	*r*		0.840	0.259
		P-value		< 0.001**	0.037*
	125–250 μm	*r*			0.167
		P-value			0.183
Reidh-lochan	≥ 500 μm	*r*	0.096	0.117	– 0.045
		P-value	0.413	0.315	0.705
	250–500 μm	*r*		0.505	– 0.005
		P-value		< 0.001**	0.965
	125–250 μm	*r*			– 0.003
		P-value			0.981

Pearson Correlation Coefficients (*r*) and significance levels (*P*-value) between the four different charcoal measures at each of the analysis sites. Loch an Amair: $n = 71$; Dubh-Lochan: $n = 75$ between macroscopic size fractions, $n = 69$ for microscopic; Lochan na h-Inghinn: $n = 67$ between macroscopic fractions, $n = 65$ for microscopic; Reidh-lochan: $n = 75$ between macroscopic fractions, $n = 73$ for microscopic.
*Significant at the 0.05 level (2-tailed).
**Significant at the 0.01 level (2-tailed).

Glen begins around 4600 cal. BP with some evidence of agricultural land use following 2500 cal. BP. The similarity of the pattern of burning observed at these diverse sites across such a large geographic region is indicative of the larger-scale burning of vegetation. Additionally, the elevated charcoal levels revealed during the early Holocene (Figures 2–4) further corroborate the assertion that the macroscopic charcoal record at these sites is derived from broad-scale burning of vegetation and not from local human occupation and domestic fires.

Table 4 Summary of one-way ANOVA showing the significance of differences in mean charcoal abundance of the four size fractions among pollen assemblage zones at each analysis site

Charcoal size fraction	No. of pollen assemblage zones	d.f.	*F*	*P*-value
Loch an Amair				
≥ 500 μm	4	3, 67	9.325	< 0.001**
250–500 μm	4	3, 67	21.516	< 0.001**
125–250 μm	4	3, 67	28.215	< 0.001**
Microscopic	4	3, 69	9.846	< 0.001**
Dubh-Lochan				
≥ 500 μm	5	4, 70	2.513	0.049*
250–500 μm	5	4, 70	2.985	0.025*
125–250 μm	5	4, 70	3.140	0.020*
Microscopic	5	4, 70	2.921	0.027*
Lochan na h-Inghinn				
≥ 500 μm	6	5, 61	4.649	0.001**
250–500 μm	6	5, 61	17.660	< 0.001**
125–250 μm	6	5, 61	21.216	< 0.001**
Microscopic	6	5, 63	3.660	0.006**
Reidh-lochan				
≥ 500 μm	4	3, 71	0.581	0.629
250–500 μm	4	3, 71	4.037	0.010**
125–250 μm	4	3, 71	217.894	< 0.001**
Microscopic	4	3, 71	2.159	0.100

*Significant at the 0.05 level.
**Significant at the 0.01 level.

Fire and vegetation change

The charcoal and pollen results (Figures 2–5) reveal that pine abundance in the Highlands is not related to fire history. A summary diagram (Figure 6) of the Holocene changes in charcoal accumulation (125–250 μm), *Pinus sylvestris* pollen frequency and blanket peat taxa (*Calluna vulgaris*, Cyperaceae, Poaceae and *Sphagnum*), reveals common trends across the four sites (see Froyd, 2002, for full pollen diagrams). This analysis clearly shows that Holocene pine communities in the Highlands are not fire-dependent. These results are from sites located throughout the Highlands, all with very different pine community histories. Elevated charcoal levels do not follow any of the hypothesized patterns of fire-dependency for pine. Increased charcoal does not immediately precede pine establishment, coincide with periods of increased pine abundance nor show a significant change when pine populations decline (Figure 6).

Pine has been constantly present at Loch an Amair (Figure 6) in Glen Affric from 8300 cal. BP to the present. Pine abundance is not related to the charcoal record: pinewoods occur throughout a 6000-yr period when there is little burning at the site and in equal abundance over the last 2000 years when charcoal levels increased. Similarly, pine presence is unrelated to charcoal abundance at Dubh-Lochan in the Great Glen region (Figure 6). The Dubh-Lochan sequence reveals one of the most clear, dramatic declines of pine woodland in

Table 5 Correlations between charcoal, *Pinus sylvestris* and *Calluna vulgaris* pollen concentrations

Site	Charcoal		*Pinus sylvestris*	*Calluna vulgaris*
Loch an Amair	≥ 500 μm	r	0.070	0.580
		P-value	0.559	< 0.001**
	250–500 μm	r	0.029	0.638
		P-value	0.810	< 0.001**
	125–250 μm	r	– 0.018	0.716
		P-value	0.880	< 0.001**
	Microscopic	r	– 0.058	0.397
		P-value	0.627	0.001**
Dubh-Lochan	≥ 500 μm	r	– 0.139	0.525
		P-value	0.255	< 0.001**
	250–500 μm	r	– 0.182	0.518
		P-value	0.135	< 0.001**
	125–250 μm	r	– 0.174	0.549
		P-value	0.153	< 0.001**
	Microscopic	r	– 0.135	0.061
		P-value	0.249	0.604
Lochan na h-Inghinn	≥ 500 μm	r	– 0.069	0.307
		P-value	0.586	0.013*
	250–500 μm	r	0.262	0.513
		P-value	0.035*	< 0.001**
	125–250 μm	r	0.240	0.585
		P-value	0.054	< 0.001**
	Microscopic	r	– 0.031	0.515
		P-value	0.798	< 0.001**
Reidh-lochan	≥ 500 μm	r	– 0.052	0.003
		P-value	0.662	0.982
	250–500 μm	r	– 0.102	0.236
		P-value	0.392	0.045*
	125–250 μm	r	– 0.157	0.310
		P-value	0.184	0.008**
	Microscopic	r	0.307	0.286
		P-value	0.007**	0.013*

Loch an Amair: macroscopic size fractions $n = 71$, microscopic $n = 73$; Dubh-Lochan: macroscopic ($n = 69$), microscopic ($n = 75$); Lochan na h-Inghinn: macroscopic ($n = 65$), microscopic ($n = 69$); Reidh-lochan: macroscopic ($n = 73$), microscopic ($n = 75$).
*Significant at the 0.05 level (2-tailed).
**Significant at the 0.01 level (2-tailed).

the Scottish Highlands, with *Pinus sylvestris* pollen levels decreasing rapidly after 7300 cal. BP. Little charcoal is present at Dubh-Lochan either directly preceding or throughout the period of pine woodland dominance at the site, nor are there any significant changes in charcoal abundance associated with declining pine pollen levels.

There is also no relationship between charcoal and pine abundance at Reidh-lochan in northeast Scotland, where increasing charcoal values begin following the final reduction in *Pinus sylvestris* pollen frequencies (Figure 6). The only site that does exhibit a possible relationship is Lochan na h-Inghinn on the northwest coast. Pine was, at best, only a minor component of the vegetation at Lochan na h-Inghinn, with pollen frequencies reaching up to 10–20% during the early Holocene. The presence of fossil pine stomata in the sediments indicates that, despite the low pollen levels, the species has been locally present at the site (Froyd, 2002). Elevated charcoal levels throughout the early Holocene coincide with increased pine pollen frequencies at Lochan na h-Inghinn (Figure 6), although this also corresponds to a period of early mire development. Elevated levels of *Pteridium aquilinum* spores also occur throughout the same period (Froyd, 2002), further indication of actual local burning within the catchment as this pioneer species readily establishes on burned sites and can exhibit a quick growth response in open, burned-over habitats (Page, 1982).

All four sites reveal a broadly similar pattern of burning, with some exception at Reidh-lochan. Charcoal accumulation levels are generally elevated during the early Holocene (the early Holocene period is missing from the Reidh-lochan sequence), followed by minimal burning throughout the mid-Holocene. Burning then increases within each of the catchments coincident with evidence of increasing mire development, although the timing of this expansion is variable (Figure 6). Increasing heathland/mire development, and the corresponding increase in charcoal levels, is represented by the uppermost pollen assemblage zones at each site: Pollen Zone 4 at Loch an Amair (2200 cal. BP), Zone 5 at Dubh-Lochan (4600 cal. BP); Zone 6 at Lochan na h-Inghinn (600 cal. BP), and Zones 2–4 at Reidh-lochan (beginning at 4800 cal. BP).

Elevated charcoal levels persist at three of the four sites, but macroscopic charcoal decreases at the top of the Reidh-lochan sequence despite the continued development of blanket mire (Figure 6). Microscopic charcoal levels at Reidh-lochan do not show a similar pattern of decline (Figure 5). It is unclear why macroscopic charcoal levels drop-off over the last 2800 years at Reidh-lochan, while mire development at the site continues. There are no significant vegetation or sedimentological changes associated with the reduction in charcoal at this time, although evidence of arable agriculture does increase after 2000 cal. BP (Froyd, 2002) and the reduction in charcoal could possibly be a result of changing land use.

Table 6 Comparison of charcoal accumulation rates between sites investigated in this study and lake sedimentary sequences in areas of known wildfire activity

Site	Charcoal size class	Typical peak accum. rates* (particles/cm^2 per yr)	Max. accum. rate*	Reference
Loch an Amair	125–250 μm	1.5–4.5	6	This study
Dubh-Lochan	125–250 μm	1–4	5	This study
Lochan na h-Inghinn	125–250 μm	2–10	12	This study
Reidh-lochan	125–250 μm	0.5–2.5	2.75	This study
W. Thumb, Yellowstone, USA	125–250 μm	3–7	8	Millspaugh and Whitlock (1995)
Duck, Yellowstone, USA	125–250 μm	3–11	20	Millspaugh and Whitlock (1995)
Mallard, Yellowstone, USA	125–250 μm	3–8	13	Millspaugh and Whitlock (1995)
Dryad, Yellowstone, USA	125–250 μm	5–10	14	Millspaugh and Whitlock (1995)
Grizzly, Yellowstone, USA	125–250 μm	5–20	22	Millspaugh and Whitlock (1995)
Dog Lake, Brit. Col., Canada	> 150 μm	0.1–1.0	3	Hallett and Walker (2000)
Frozen Lake, Brit. Col., Canada	> 125 μm	0.2–0.8	1.0	Hallett *et al.* (2003)
Mount Barr, Brit. Col., Canada	> 125 μm	0.2–5.0	10	Hallett *et al.* (2003)
Bluff Lake, California, USA	> 125 μm	0.5–2.0	10	Mohr *et al.* (2000)
Crater Lake, California, USA	> 125 μm	0.5–1.5	1.75	Mohr *et al.* (2000)

*Values are only approximations based on visual estimates from published diagrams.

Reidh-lochan differs in a number of ways from the other sites examined in this study. The degree of human impact that is present is much higher than at the other sites. Also, while Loch an Amair, Dubh-Lochan and Lochan na h-Inghinn have remained largely forested throughout the Holocene, blanket mire communities have predominated at Reidh-lochan (Figure 5), with the early inception of mire development at the site coincident with palynological indication of anthropogenic activity. Overall, macroscopic charcoal accumulation rates at Reidh-lochan are the lowest of the four sites examined, and there is little charcoal in the ≥ 500 μm size fraction. Results are also more variable between charcoal size fractions than at the other sites (Table 3). A potential contributing factor to explain the more variable results at Reidh-lochan may be the site's flat topography, with less opportunity for secondary charcoal input to the lake. The occurrence of the least amount of charcoal at the site with the most evidence of anthropogenic impact of the four sites examined further supports the assertion that the Highland charcoal record is not an artefact of domestic fires.

The results presented here indicate that fire was not the deterministic factor for the survival of pine in the Highlands. Fire occurrence does not appear to be related to either the establishment or maintenance of *Pinus sylvestris* woodland. No relationship was found between charcoal and *Pinus sylvestris* at Loch an Amair or Dubh-Lochan, the two sites examined with abundant *Pinus sylvestris* populations (Figure 6, Table 5). Charcoal abundance is, however, significantly related to the overall pattern of vegetation change at each of the four sites (Table 4). Rather than pine woodland, fire appears to correspond instead with the development of heathland and blanket mire communities. Charcoal abundance was found to be significantly correlated with *Calluna vulgaris* pollen concentrations at all four sites (Table 5), and charcoal abundance was significantly higher in the uppermost vegetation zones characterized by increasing frequencies of mire taxa at Loch an Amair, Dubh-Lochan and Lochan na h-Inghinn. The elevated charcoal levels throughout the early Holocene at Lochan na h-Inghinn (Figure 6) during a period of early mire development further support the indication of a direct relationship between fire occurrence and mire/heathland development.

Both Fossitt (1990) and Edwards (1996) note the link between charcoal and the presence of *Calluna vulgaris* communities at sites in the Western and Northern Isles. Dodson and Bradshaw (1987) and Odgaard (1994) also describe the association between charcoal and *Calluna* heathland development at sites in western Ireland and Denmark, respectively. Review of the few detailed charcoal analyses that exist for the Scottish mainland support the pattern revealed by this investigation. Charcoal profiles within bog sequences at Torran Beithe (Davies, 1999), Glen Torridon and Glen Carron (Anderson, 1998) show increased charcoal frequencies occurring subsequent to declines in pine populations at these sites. Microscopic charcoal analysed from a lochan in Achany Glen (Smith, 1996), near Lairg, appears to be more directly linked to the occurrence of *Calluna vulgaris* rather than that of pine.

Fossitt (1990) concluded from the examination of microscopic charcoal in four sequences from the Western Isles that burning in the area was highly variable, both spatially and temporally. Evidence presented here reveals some general trends in the Holocene occurrence of fire on the Scottish mainland. Fire was present at a moderate level during the early Holocene, after which time charcoal abundance drops to minimal values. Fire consistently became more abundant on the landscape with the spread of heathland and blanket bog vegetation. Separating the effect of natural fires within these plant communities from anthropogenic burning is problematic. However, the association between charcoal and the period of mire development during the early Holocene at Lochan na h-Inghinn, prior to any evidence of human impact, indicates that natural burning within mire communities did occur. The degree to which anthropogenic impact is responsible for increased mire expansion and/or burning remains to be disentangled. Two of the sites examined in this study show very little evidence of human impact and the other two exhibit varying degrees of agricultural development, yet all four sites show an increase in charcoal abundance coincident with mire expansion. Further investigation is warranted into the causal mechanisms behind this relationship. It is not yet clear whether increased fire activity caused the expansion of heathland/mire communities or *vice versa*.

Charcoal measures

The four different charcoal measures were compared in order to determine the most accurate and expedient methodology for future fire history assessments in Scotland. A close correspondence was found among the macroscopic charcoal

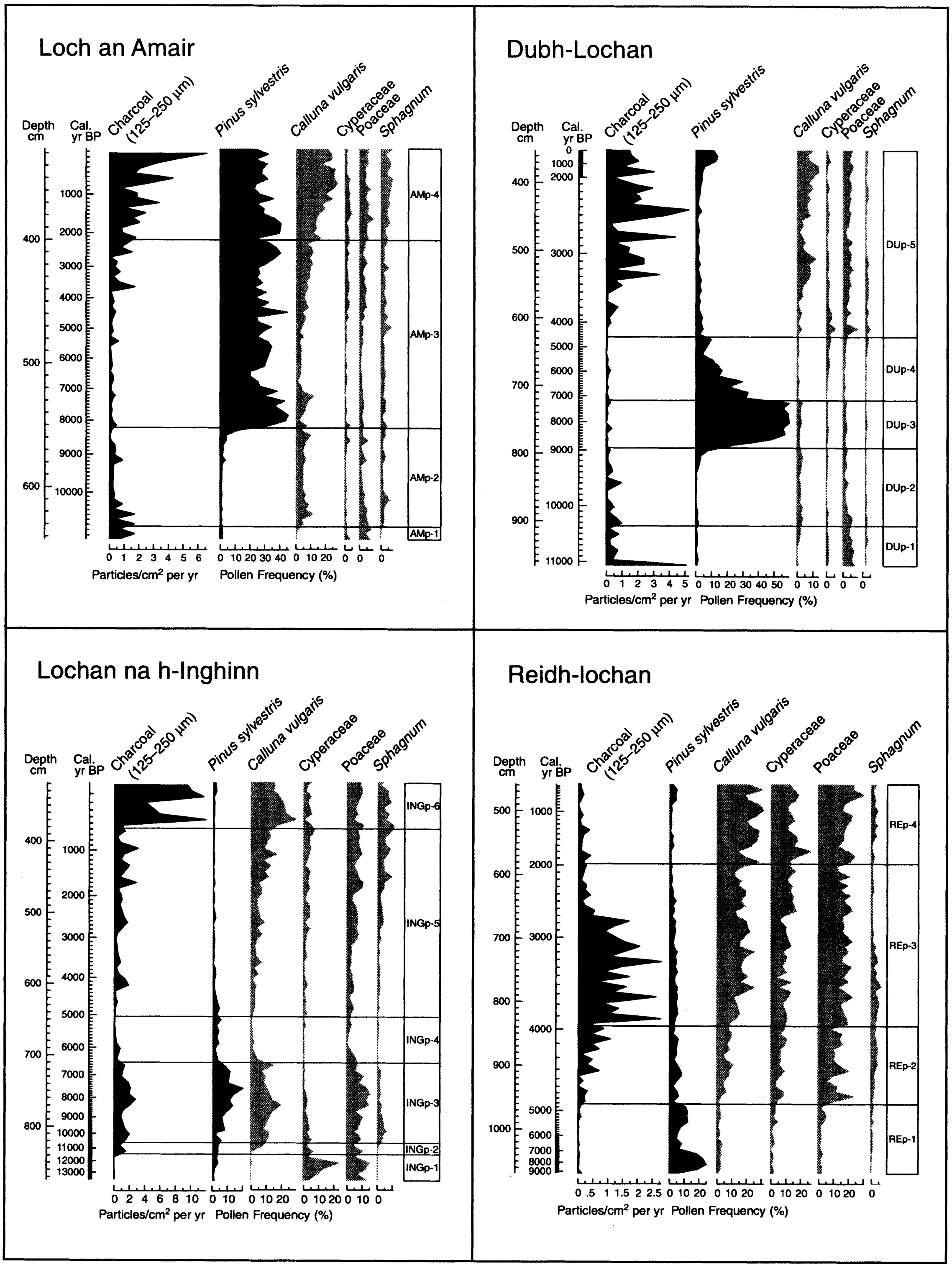

Figure 6 Summary diagram of changes in macroscopic charcoal (125–250 µm) accumulation rate, *Pinus sylvestris* pollen frequency and blanket peat taxa over time at each site. Pollen and spore frequencies are expressed as percentages of the calculation sum. All sites are plotted against sediment depth (cm) as measured from the lake surface, timescale axes (cal. BP) are also displayed

size fractions, corroborating evidence obtained from temperate coniferous forests in North America (Millspaugh and Whitlock, 1995; Long *et al.*, 1998; Mohr *et al.*, 2000). All of the macroscopic charcoal size fractions analysed (≥ 500 µm, 250–500 µm and 125–250 µm) were significantly correlated ($P \leq 0.001$) at three of the four sites (Table 3). The fourth site, Reidh-lochan, revealed significant correlations amongst the smaller macroscopic size fractions (Table 3), but low occurrence of the ≥ 500 µm fraction precluded adequate assessment. The generally low abundance of charcoal particles ≥ 500 µm indicates that accuracy may be sacrificed in fire history assessments based solely on the utilization of larger size fractions. The close correlation ($P \leq 0.001$) between the 125–250 µm and 250–500 µm classes at all four of the sites examined – even at Reidh-lochan, the site with lowest overall abundance of charcoal – indicates that information about fire occurrence in the Highlands at the current level of resolution may have been accurately, yet more expediently, obtained through the analysis of the less abundant 250–500 µm size fraction alone. Raw counts of this size fraction are an order of magnitude lower than in the 125–250 μm class, thereby greatly reducing analysis time, and the larger particles have the additional advantage of being more easily definitively identified as charcoal.

Microscopic charcoal was correlated with the macroscopic measures at only two of the four sites, Loch an Amair and Dubh-Lochan (Table 3). Results at Lochan na h-Inghinn were variable: microscopic charcoal was found to be correlated with the 250–500 μm macroscopic size fraction ($P \leq 0.05$), but unrelated to the other size classes. Microscopic and macroscopic charcoal at Reidh-lochan are statistically unrelated (Table 3). The lack of consistent correspondence between the microscopic and macroscopic measures at the four sites demonstrates that microscopic charcoal cannot confidently be utilized as a measure of local catchment-scale burning in the Highlands. Further investigation is needed in order to understand what the microscopic charcoal signal represents, ie, what proportion is the result of regional versus local fires, and what conditions may affect this.

Conclusions

The charcoal results indicate that landscape-level burning of vegetation did occur in the Scottish Highlands throughout the course of the Holocene. Macroscopic charcoal levels were found to be comparable with those occurring in lake sediments within regions of known wildfire activity. This evidence, in conjunction with the consistent pattern of burning revealed across the four disparate analysis sites and the direct relationship observed between charcoal and vegetation change all indicate the occurrence of broad-scale fire. The abundance of pine, however, was found not to be related to fire history as had previously been hypothesized (Bradshaw, 1993). Instead, fire in the Highlands appears to be predominantly linked to the development of heath and blanket mire communities. Different size fractions of macroscopic charcoal were found to be strongly correlated at all of the sites examined. Microscopic charcoal abundance, however, was more variable and was therefore determined to be a less accurate measure of local catchment-scale burning within the region.

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