# Moorland Fire History from Microscopic Charcoal in Soils and Lake Sediments

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by

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## Abstract

Microscopic charcoal analyses of sediment cores are used widely by palaeoecologists for reconstructing proxy records of past fire activity. Few studies, however, have reconstructed fire histories from UK and Irish moorland environments, a rather surprising situation considering the fact that much of the heather-dominated moorland in the UK and Ireland has been managed and maintained using fire for many centuries, and in some instances millennia. This thesis addresses the main issues regarding the use and applicability of microscopic charcoal analyses in moorland contexts.

The literature pertaining to the theory and practical application of microscopic charcoal analyses is comprehensively reviewed, and all aspects of microscopic charcoal analysis, from charcoal production through to the interpretation of sediment charcoal profiles, are discussed and wherever possible related to their applicability in moorland contexts.

An investigation of the taphonomy of microscopic charcoal around small moorland fires was conducted in order to provide an appreciation of the processes of charcoal production and the extent of charcoal particle dispersal. The results suggest that small moorland fires produce differential quantities of charcoal particles of different size ranges, smaller particles are produced in significantly greater quantities than progressively larger ones. The majority of charcoal particles produced by small muirburns are deposited locally, within approximately 70-100 m of parent fires, and the wind direction at the time of the fire may be a key factor determining the dispersal of microscopic charcoal particles, the majority being deposited down-wind of fires, few are dispersed laterally or into the wind.

A microscopic charcoal quantification technique was developed to reconstruct extended (>50 year) fire histories from moorland soil profiles. A number of fire histories from mor humus-rich moorland soil cores of approximately several centuries duration were reconstructed. Fossil charcoal assemblages produced by *in situ* fires were distinguished from those produced by nearby *ex situ* fires on the basis of differences in gross charcoal abundance and charcoal size class distributions. Charcoal assemblages produced by *in situ* fires are determinable from those produced by *ex situ* fires because they generally contain a greater total abundance of charcoal particles and higher proportions of medium to large particles.

Microscopic charcoal analyses of lake sediment cores from seven UK and Irish moorland catchments were used to reconstruct long-term (>100 year) fire histories. The reconstructed fire histories were used to assess whether changes in fire activity in the catchments may have been responsible for initiating past episodes of peat erosion, inferred from loss on ignition measurements, and declines in *Calluna* cover, inferred from pollen analyses, evident at all of the sites. The results suggest that moorland burning may have been an influential factor contributing to the initiation of peat erosion at only one of the seven sites studied. Similarly, fire activity was only significantly related to the loss of *Calluna* at two of the seven sites studied.

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## Microscopic charcoal analysis of moorland soils and lake sediments.

### 1.1 Introduction

The *Calluna vulgaris*-dominated moorlands of Britain and Ireland represent ecosystems of national and international importance for both their ecological and economic value (Ratcliffe & Thompson, 1988; Sydes & Miller, 1988; Thompson *et al.*, 1995). Britain's heather-dominated moorland not only supports many rare plant communities (Rodwell, 1991) and bird species, e.g. golden plover (*Pluvialis apricaria*) and merlin (*Falco columbarius*), but represents a uniquely sustainable resource in the upland agricultural economy for sheep, grouse and deer production (Usher & Thompson, 1993).

The conservation value of moorland ecosystems is reflected in the vast amount of research which has been conducted on them, and particularly into the ecology of *Calluna vulgaris* (e.g. Gimingham, 1960; Gimingham, 1972). Fire has been used to manage and maintain *Calluna vulgaris*-dominated moorland for many centuries (Gimingham, 1970) and accordingly the relationships between fire and the ecology of *Calluna vulgaris* has received a great deal of study (*e.g.* Kayll, 1966; Mallik & Gimingham, 1983; Hobbs & Gimingham, 1984; Maltby *et al.*, 1990). However, the vast majority of this research has been of a short-term nature, concentrating on the dynamics of communities over time-scales of rarely longer than several decades. Observations made over such short time-scales are insufficient for predicting the long-term effects of anthropogenically imposed fire regimes, and consequently the long-term dynamics of moorland vegetation are relatively poorly understood (Stevenson & Thompson, 1993; Legg, 1995).

An increasing volume of research suggests that British and Irish *Calluna*-dominated moorland communities are in decline (Andersen & Yalden, 1981; Sydes & Miller, 1988; NCC, 1987; Thompson *et al.*, 1995), and may have been for at least several centuries (Stevenson & Thompson, 1993). Britain is not alone in experiencing declines in heather-dominated vegetation, Sweden, Denmark, The Netherlands, Belgium, Germany and France have also suffered considerable losses in area over the past century (Gimingham, 1977). In addition, upland moorland ecosystems are also suffering extensive degradation by peat erosion, a further problem proven to have been occurring over prolonged periods of time, and in some instances for millennia (McGreal & Larmour, 1979; Bradshaw & McGee, 1988). The long-term nature of these problems dictates that long-term perspectives need to be adopted if their causes are to be elucidated.

Palaeoecological techniques, palynology and microscopic charcoal analyses, provide the means to reconstruct long-term vegetation and fire histories (Moore *et al.*, 1991; Patterson *et al.*, 1987). Fossil pollen and charcoal analyses have provided valuable insights into landscape and vegetation community dynamics in a wide range of environments (*e.g.* Swain, 1973; Singh *et al.*, 1974; Griffin & Goldberg, 1975; Heusser, 1989). However, considering the semi-natural nature and dependency of most heather-dominated communities on muirburn management for their maintenance (Gimingham, 1970; Gimingham, 1972) moorland ecosystems have received little palaeoenvironmental attention (*e.g.* Iversen, 1941, 1969; Odgaard, 1992, 1994; Charman, 1992).

### 1.2 Thesis outline

The work described in this thesis is an attempt to determine what can or cannot be deduced from fire histories derived from microscopic fossil charcoal analyses in soil and lake sediments from moorland contexts. Moorland environments represent potentially complex environments in which to reconstruct fire histories from sediment records. Muirburn management of moorland vegetation, which involves the periodic burning of small patches of heather in rotation (Muirburn Working Party, 1977), results in relatively small quantities of microscopic charcoal being produced by large numbers of isolated, relatively low intensity, extremely short duration fires, set on an annual basis, at locations spread randomly over the moor surface. In this thesis an attempt is made to quantify and elucidate the fundamental processes of charcoal production and taphonomy around muirburns; to develop a method of reconstructing extended (>50 year) fire histories for individual locations on moors using microscopic charcoal analyses of mor humus soil profiles; and to assess whether changes in the long-term (up to 1000 year) burning regimes of a number of UK and Irish heather-dominated catchments may have been responsible for causing the initiation peat erosion episodes and the protracted decline of *Calluna vulgaris* in them.

Microscopic charcoal analyses have been widely adopted by palaeoecologists and a considerable amount of research has been conducted into the theoretical tenets of, and the practicalities of conducting, such analyses. Chapter 2 of this thesis reviews the wealth of literature published on the subject of microscopic charcoal analyses. The role of this review is to provide the reader with a comprehensive introduction to the principles of microscopic charcoal analyses and background knowledge of the nature of past study in this field. The following issues are among those covered: the current level of understanding of charcoal particle production, dispersal, deposition and sedimentation processes; site selection criteria and the merits and weaknesses of soils, peats and lake sediments as depositories of charcoal records; available techniques of sediment sample preparation and charcoal quantification; and the information that can be gained from, and how to interpret sediment charcoal profiles. Throughout the review the applicability of past theory and practice to moorland environments is emphasised.

In Chapter 3 the sites and methods of analysis used for this study are described. Special attention is given to the laboratory procedures for charcoal sample preparation and quantification developed for this study. Chapter 4 outlines the methods used to develop and validate a methodology for reconstructing extended (>50 year) fire histories of individual locations on moors. The methodology was developed to enable the determination of the approximate dates when stands of heather were last burned, or the frequency and periodicity at which they have been burned over past centuries, potentially useful information in all manner of ecological studies. Analyses of aerial photographs and microscopic charcoal from mor humus soil cores are used to determine the resolution of the sediment charcoal record and to characterise how charcoal assemblages produced by *in situ* and *ex situ* fire events differ and are manifested in soil profiles. Extended histories of local fire activity are produced for a number of locations on six moorland sites in Perthshire, Scotland in order to test and validate the techniques developed.

In Chapter 5 the taphonomy of microscopic charcoal around past muirburns on a Perthshire moorland site is investigated. Aerial photographs are used to map patterns of past muirburn activity and charcoal analyses of soil cores located at known distances around the edges of dated fires are used to quantify patterns of charcoal dispersal. The processes of charcoal production by, and dispersal around, controlled heather burns are explored. The results provide important information to aid the estimation of the distances over which charcoal can be dispersed and to delimit charcoal source areas for sediment sinks in moorland areas from which fire histories may be reconstructed. The charcoal dispersal information is used in this study to inform the interpretation of the charcoal records form lake sediment cores presented in Chapters 6 and 7.

In Chapter 6 microscopic charcoal analyses and associated palaeoecological techniques of lake sediment cores are used to try and elucidate the causes of past peat erosion in seven UK and Irish moorland catchments. Of primary concern is whether excessive burning of catchment vegetation may have been instrumental in causing the inception of erosion, although a number of other possible causes are considered. Redundancy analyses (RDA; ter Braak, 1990a) are used to determine the statistical relationship between the inferred fire (charcoal) and erosion (loss on ignition) records providing a means of estimating the possible influence of fire activity as a cause of erosion.

In Chapter 7 a palaeoecological approach similar to that adopted in Chapter 6, using microscopic charcoal and pollen analyses are used to determine whether excessive heather burning may have caused declines in *Calluna vulgaris* cover in the same seven UK and Irish moorland catchments over the past four centuries. Possible alternative causes of *Calluna* cover loss are also considered. Chapter 8 provides a summary of the conclusions made throughout the research project and suggestions for further study.

# Chapter 2: Literature Review

## Abstract

A large body of literature concerning all aspects of microscopic charcoal analysis is reviewed. The processes of charcoal formation by biomass fires are described, and the current state of knowledge of microscopic charcoal dispersal, deposition and sedimentation processes is outlined and discussed in light of studies of pollen taphonomy. Site selection considerations, sediment sampling strategies and charcoal analysis techniques are discussed. Guidelines on the interpretation of microscopic charcoal profiles are also provided. Where appropriate the theories proposed and conclusions reached by past studies are assessed with respect to their applicability to charcoal analyses in moorland contexts.

## 2.1 Charcoal definition

The term 'charcoal' is taken, throughout this thesis, to represent 'an impure form of carbon produced by the incomplete combustion of biomass' (Goldberg, 1985). Two types of black carbon are produced by biomass burning, sub-micron particles formed from the vapour phase, and larger particles (> tens of microns) that reflect the structure of the burned material or the burning process, only the second category is of concern here. Charcoal is typically black, lustrous, fragile, relatively inert, and retains the form of the plant material from which it was derived (Clark, 1984; Scott & Jones, 1991). Charcoal is synonymous with char, fusain, black carbon, elemental carbon and soot referred to by other authors (Goldberg, 1985).

An explicit distinction between the carbon rich products of biomass burning and those produced by fossil fuel combustion is assumed throughout this work. Black carbon particulates formed by the high temperature combustion of fossil fuels, which are morphologically distinct from those produced by biomass burning by their spherical shape, will be referred to as 'spherical carbonaceous particles' (SCPs) not charcoal (Griffin & Goldberg, 1981; Renberg & Wik, 1985).

### 2.2 Charcoal formation

Charcoal is formed by the incomplete combustion of plant tissues under conditions of restricted oxygen (Aaron, 1980; Clark & Russell, 1981; Chandler *et al.*, 1983). Plant tissues are typically made up of cellulose, hemicellulose (together 50% to 75% of most dry plant material), lignin (15% to 35%), proteins, nucleic acids, amino acids, volatile extractables and water (which can account for up to 60% of a plant's fresh weight) (Lobert & Warnatz, 1993). The process of charcoal formation and the characteristics of the charcoal produced are closely related to the temperature and duration of combustion.

When plant tissues are burned at temperatures of up to 200°C water (completely removed at 140°C), carbon dioxide and other trace gases are evolved (Cope & Chaloner, 1985). Charcoal can be produced at these temperatures but the process requires prolonged exposure to heat (Smart & Hoffman, 1988). At temperatures between 200°C and 280°C thermal decomposition of wood produces charcoal and liberates non combustible gases. As temperatures increase to between 280°C and 500°C combustible gases (e.g. carbon monoxide, methane, and hydrogen) and volatile compounds such as tars are consumed by pyrolysis and charcoal forms as a solid residue. (Cope & Chaloner, 1985). Temperatures in excess of 500°C result in diminished charcoal preservation as much is oxidised to ash (the inorganic products of charcoal combustion composed mostly of oxides, potassium, phosphates and silicates) (Smart & Hoffman, 1988). If temperatures exceed 1100°C charcoal is oxidised directly to carbon monoxide and hydrogen (Cope & Chaloner, 1985).

#### 2.2.1 Charcoal formation during moorland fires

Moorland fires are surface fires which spread by flaming combustion of vegetation on or near the land surface fuelled by litter (fallen dead vegetation components) and mosses, standing dead fuels (woody shrub stems and grasses), and live ericaceous shrubs, grasses and other plant material (Albini, 1993). Typical temperatures attained are between 250°C and 670°C, although temperatures approaching 900°C have been recorded during particularly intense fires (Kayll, 1966; Whittaker, 1961; Kenworthy, 1963). Peak temperatures, however, are generally only maintained for periods of less than 60 seconds duration (Kenworthy, 1963; Hobbs & Gimingham, 1987a), and complete combustion of all woody material is rarely achieved. In most instances a period of smouldering or 'glowing' combustion follows the initial flaming stage, the embers being fanned by the wind until sufficient heat is lost that combustion ceases and beds of partially charred and unburned fuel are left (Albini, 1993). It is during this period of glowing combustion that fuel decomposition and charcoal formation are greatest.

The quantity and properties of the charcoal produced by moorland fires depend on the behaviour and characteristics of the parent fire. Fire intensity is closely related to fuel structure and density, and thus the age of vegetation stands. The most intense moorland fires are experienced in 25 - 26 year old *Calluna* stands which are generally composed of densely structured live woody stems with abundant foliage and significant amounts of dead woody material and litter, excellent fuel for intense combustion (Kayll, 1966). Younger stands lack the high densities of woody material and litter, and older degenerate stands the fine stem and leaf components necessary to sustain high temperatures. Charcoal production is likely to be greatest in vegetation stands aged between 20-30 years.

The moisture content of plant material has a great influence on its performance as a fuel because plant water must be driven-off, a process demanding much energy, before ignition can occur. Green plant material in heather stands impedes the burning efficiency, retarding flaming pyrolysis and enhancing smouldering combustion (Lobert & Warantz, 1993). Indeed, if heather stands did not contain significant components of dead woody material and litter they would not burn effectively. Kayll (1966) found that the high moisture condition of fuels during spring retarded fire efficiency to the extent that only 30% was consumed, in contrast autumn fires, under drier fuel conditions, consumed approximately 93% of available vegetation. More charcoal is likely to be formed by the burning of drier, but not tinder dry, vegetation.

Methods of burning can influence charcoal production. The majority of muirburns are allowed to run with the wind (heading fires) (Muirburn Working Party, 1977; Phillips *et al.*, 1993). During heading fires the flames at the fire front bend towards the unignited fuel and increase the rate of heat transfer substantially. As a result, the fire spreads much more rapidly in the direction of the wind than against or perpendicular to it (Albini, 1993). Heading fires produce large flames but because they move relatively quickly have a tendency to incompletely oxidise larger diameter fuel components (Lobert & Warantz, 1993). Burns littered with large quantities of superficially scorched heather stems and completely charred leaf and fine debris are typical of heading fires. As wind speeds increase and fires move more quickly they become less efficient and consume even less fuel, in strong winds often only the crowns of shrubs are ignited and most of the woody material is left unconsumed (Hobbs & Gimingham, 1984). When burns are conducted into the wind (backing fires) the flames bend back into the burning zone, decreasing radiant heating of nearby unignited fuel. As a consequence backing fires have relatively small flames and slow rates of fire spread, but combustion is more efficient (Albini, 1993; Lobert & Warantz, 1993). Backing fires generally produce more charcoal than heading fires.

Topography can also influence the burning behaviour of fires, particularly small fires like muirburns. A burn behaves like a backing fire if it proceeds down-slope, burning efficiently, while an up-slope fire moves faster consuming the fuel more like a wind-driven fire. This is because the flames at the fire edge tend to be vertical and on the up-slope the angle between the flame and the vegetation is less than 90 degrees, hence the rate of heat transfer to the unignited fuel is great. On the downslope, the angle between the flames and the unignited fuel is more than 90 degrees and fire spread is retarded (Hobbs & Gimingham, 1987; Lobert & Warantz, 1993; Albini, 1993).

## 2.3 Charcoal taphonomy

The processes and mechanisms of pollen dispersal and deposition have received a great deal of both experimental and theoretical attention and as a consequence are relatively well understood (Moore, Webb, & Collinson, 1991; Jackson, 1994). Charcoal taphonomy, however, has been greatly neglected and remains as perhaps the single most important factor limiting the full and unequivocal interpretation of sedimentary charcoal profiles (Battson & Cawker, 1983; Clark, 1983; Anderson & Davis, 1986). Greater appreciation of charcoal source areas and the processes of charcoal dispersal and sedimentation are needed.

In the following section the physics of charcoal dispersal in the atmosphere are outlined briefly. A selection of models and studies of charcoal and pollen taphonomy are then reviewed. The models are evaluated for theories and concepts which can be applied to understanding the mechanisms of microscopic charcoal dispersal and deposition.

### 2.3.1 The physics of charcoal dispersal in the atmosphere

All particles suspended in the atmosphere are subject to the force of gravity, to a buoyant force, and to drag forces which combine to govern their motion (Chamberlain, 1975). The deposition of smooth spherical particles can be modelled because terminal velocities, stopping distances and trajectories can be determined using Stoke's Law (Gregory, 1945; Chamberlain, 1975). However, it is much more difficult to provide models of charcoal particulate dispersal and deposition because of their angular shapes, differing sizes, and variable densities. Rather than following predictable trajectories elongated particles tend to fall more horizontally with their greatest surface area presented to the resistance of the air, sometimes falling more slowly than spherical particles of the same volume, and sometimes more quickly (Buller, 1909; Fuchs, 1964). Generally speaking, however, charcoal particles should settle and be sorted on the basis of their 'fall velocities', a function dependent mainly upon size and density but also on shape and surface roughness. Large heavy particles and those with high volume to surface ratios will tend to be deposited more quickly than smaller, lighter ones (Walker, 1971; Patterson *et al.*, 1987).

It is likely, although as yet unproven, that charcoal deposition away from a source will approximate a leptokurtic curve, similar to that observed for pollen, spores, dusts, and other particulates (Colwell, 1951; Green & Lane, 1964; Turner, 1964; Janssen, 1966, 1984; Raynor *et al.*, 1968, 1972a, 1972b, 1975, 1976; Prentice, 1985; Okubu & Levin, 1989) (a supposition strengthened by observations of charcoal dispersal made in this study, see Figure 5.5). Charcoal concentrations decrease rapidly away from the production source and then the concentrations deposited on the ground remain relatively steady but low with increasing distance. Deposition curves for particles of different sizes will vary slightly, rates of deposition with increasing distance being more pronounced for larger particles than progressively smaller ones (Walker, 1971).

In addition to the vertical force of gravity, the dispersal and deposition patterns of particles are also complicated by the forces of wind. Wind is predominantly a horizontal force and is characteristically turbulent rather than laminar in motion, particles are thus to some extent diffused in all directions, both vertically and laterally, as well as in a downwind direction (Gregory, 1945). Experiments on pollen capture near the ground (Tauber, 1965), however, illustrate that most of the time at normal wind velocities the majority of particles do move predominantly horizontally and in the direction of the wind, *i.e.* whilst some particulates are dispersed laterally the vast majority are transported in a downwind direction.

### 2.3.2 Charcoal dispersal experiments

A number of authors have sought to quantify microscopic charcoal particle dispersal from fires by conducting experimental fires and trapping the resultant particulates at varying distances away from the parent fire. The following section outlines the methods used and the results obtained.

The charcoal dispersal experiments by conducted R.L. Clark represent the most thorough investigation of the subject to date (Clark, 1983). To assess the dispersal distances of charcoal particles of different sizes from bush fires Clark laid microscope slides coated with a thin film of petroleum jelly out on the ground along transects at 10, 20, 40 and 80 metre distances from the edges of ten controlled burns. All charcoal particles of minimum dimension >6.5 μm trapped on the slides were counted and tallied into size classes. The concentration of charcoal particles decreased with distance from the burned areas and the distribution of the charcoal reflecting the wind direction at the time of the fires, the majority being deposited downwind. The reduction in the numbers of charcoal particles with distance from the fires was not due to larger particles falling out closer to the experimental area, but to fewer particles of all sizes travelling greater distances. Neither the area burned or the type of the fire were reflected in the numbers of charcoal particles collected (Clark, 1983).

In an additional experiment two hundred and twenty-eight microscope slides coated in petroleum jelly were laid out in transects, at distances ranging from 5 metres to 3.85 kilometres, away from the edge of another controlled fire to gain further information about the long distance dispersal of charcoal particles in smoke. The areas of charcoal deposited on each slide were quantified using the point count method (Clark, 1982). Abundant charcoal was only deposited on the downwind edge of the fire, even at a distance of only 5-15 metres from the upwind edge of the fire charcoal deposition was minimal. Apart from on the slides around the fire edge no significant correlation between the charcoal area and distance from the fire was found. The deposition of larger particles (>5 μm) from the smoke was negligible beyond somewhere between 0.1 km - 1 km (the poor resolution is attributable to the low density of the sampling network) (Clark, 1983).

In a further experiment Rotorod air samplers were used to sample smoke particles from a grass-fire whilst it burned in order to assess the sizes and abundance of the particulates produced and dispersed. Although strong winds carried the smoke ahead of the fire the concentration of larger particles (>5 μm) was only high immediately in front of the fire and fell off rapidly (Clark, 1983).

Water samples taken from the Wallagaraugh River both before and after a large, high intensity forest fire in it's catchment were analysed for charcoal particles to determine the importance of streams for charcoal transport. Significant amounts of charcoal were only washed off the catchment in the first post-fire rainfall events, with the highest concentrations conveyed at the beginning of the events. The results suggesting that particles initially deposited on the ground surface are resistant to further redistribution (Clark, 1983).

Evans & Allen (1971) conducted charcoal particle dispersal experiments as part of a study of nutrient losses in the smoke from heather burns. Three artificial burns comprising of 50 kg quantities of cut heather were set on fine days with slight breezes (Beaufort Scale 1-2). Large sheets of polyethylene were spread out and secured downwind of the fires at distances of 10, 20, 40, 80 and 120 metres to act as aerosol traps. After the fires the deposits on each of the sheets were collected and weighed, however, particulate recovery was poor because much of the deposited material was blown off the sheeting before collection was possible.

Observations made during the fires, however, prompted the authors to suggest that convection currents produced by heather burns are likely to be weakly formed. Ash and other small particulates only 'float' short distances before settling, and that much of the ash produced during actual moor burns would be retained by the uneven ground and residual unburnt debris. Very severe burn conditions are necessary to generate intense convection currents which could carry fine smoke particles into the higher air stream and disperse them widely within and beyond the limits of the moor (Evans & Allen, 1971).

Wein, Burzynski, Sreenisva, & Tolonen, (1987) also conducted experiments to determine how far charcoal particles were carried by the wind during vegetation fires. Two experimental burns were set, one in a wind speed of 5 km/h and the second in a stronger wind of approximately 20 km/h. Glass test tubes fitted with 60 ml plastic funnels (mouth diameters of 6 cm) were buried so that their tops were flush with the ground surface to act as traps to capture dispersed particulates. The test tubes were arranged at 100 m intervals along a 1 km transect from the down wind edge of the fire. Following the fires the charcoal in the traps was quantified in five size classes (100-2800, 2800-44400, 44400-135800, 135800-277200, & >277200 $\mu m^2$).

Particle size and the number of particles per size class were found to be indirectly proportional to the distance from the fire front. Few particles in the largest three size classes were recovered, with a wind speed of 5 km/h a few were found up to 0.4 km from the fire and a few were carried further by the stronger wind. The smaller particles (<44400 $\mu m^2$) were still represented 1 km from the fire but their abundance also declined as distance increased.

### 2.3.3 Models of charcoal taphonomy

The processes of charcoal particulate dispersal are obviously complex, however, success in explaining patterns of pollen dispersal using theoretical models (Bradshaw & Webb, 1985; Prentice, 1985, 1988; Jackson, 1990, 1991), suggest that it may be possible to model charcoal taphonomy (Patterson *et al.*, 1987; Clark, 1988). Such theories could provide much valuable information about sedimentary charcoal assemblages and how they record evidence of fire (Tauber, 1965; Prentice, 1985; Clark; 1988). The following models of charcoal dispersal from biomass fires have been proposed.

*Patterson, Edwards, & Maguire model (1987)*

Patterson *et al.* (1987) proposed a theoretical model of charcoal particle dispersal during fires based upon the theories of pollen taphonomy developed by Tauber (1965) and Jacobson & Bradshaw (1981), and the sand dispersal theories of Bagnold (1941). Two fundamental assumptions underlie the model: (i) that charcoal dispersal conforms to the 'distance-decay principle', *i.e.* that with increasing distance from a fire the quantity and size of charcoal particles decreases, and (ii) that equal quantities of small, medium and large particles are produced by each fire event. The first assumption conforms well with accepted theory, however, data presented in Chapter 5 of this thesis casts doubt upon the validity of the second assumption, a consideration which may have important implications for the interpretation of charcoal assemblages..

In the absence of wind Patterson *et al.* (1987) theorised that charcoal particles are dispersed equally in all directions, that the largest quantities are deposited close to the fire, and that the average size of particles decreases away from the fire edge. Under windy conditions it is proposed that the majority of the charcoal produced will be dispersed in a downwind direction and little is transported to any significant distance into the wind. High wind speeds increase the distances over which particles are dispersed, particularly with regard to smaller particles which may be distributed over significantly greater distances than under still conditions (Patterson *et al.*, 1987). These theories agree with the results of experiments conducted by Clark (1983) and Wein *et al.* (1987).

The authors acknowledge that the model presents a very simplified view, however, it does provide a clear outline of a number of fundamental principles of charcoal taphonomy which have been widely adopted by subsequent analysts.

*J.S. Clark 'skip distance' model (1988a)*

J.S. Clark (1988a) presented an excellent theoretical treatment of the mechanisms governing charcoal particulate dispersal and transport by applying particle motion theories from studies of dust and sand (Bagnold, 1941; Foda, 1983; Greeley & Iversen, 1985). He focused on aeolian processes believing surface runoff to be relatively unimportant as a mechanism for transporting charcoal to lake sediments (Clark, 1988a).

Clark theorised that during a fire particulate dispersal distances are a function of particle size, fire temperature (the principle determinant of the height of the convective current formed), and wind speed. Graphs were used to show the relative 'skip distances' (the distance between the point of initial suspension of a particle in the atmosphere and the point of impact back on the ground surface) of different sized particles lofted to variable heights by convective currents (Clark, 1988).

The principal conclusions reached by Clark (1988a) were as follows: (i) that smaller particles generally travel much further than larger ones before settling back to the ground. Pollen slide size charcoal (>90% of which is 5-20 μm in length) behave like dust in the atmosphere and can be dispersed over subcontinental or global ranges if lofted to a sufficient altitude (Patterson *et al.*, 1987). Charcoal particles falling within the range of sand or larger particulates (50-10,000 μm in length) require high surface wind speeds to lift them from the surface into suspension, and if suspended are transported much shorter distances than considerably smaller particles; and (ii) that there is almost always a finite 'skip distance' for the bulk of particles in a given size range and that 'skip distances' for particles of given dimensions increase with wind speed and the height to which they were lofted (Clark, 1988a).

Following a fire, before vegetation regeneration stabilises the bare soil surface, Clark (1988a) acknowledged that charcoal fragments may be transported to sedimentary sinks by both winds and surface runoff, but believed that the importance of fluvial processes had been over estimated by previous analysts, *e.g.* Blong & Gillespie (1978) and Clark (1983). He argued that surface flow never occurs on uncompacted forest soils (Waring & Schlesinger, 1985), and that even under conditions when it does occur cohesive forces between soil and charcoal particulates would greatly reduce the amount actually transported at the low velocities and laminar flow of surface runoff (Clark, 1988a). The aeolian processes of suspension, saltation and traction, were stated to be the dominant mechanisms of post-fire charcoal transport. Charcoal particles in the range 130-150 μm in length are most readily lifted by normal winds. Cohesive forces build up between smaller particles making them less readily suspended, although if they are lifted into the atmosphere they can be dispersed widely. Particles >150 μm can be picked up by surface winds but their relatively high mass dictates that they are generally deposited nearby. A process similar to saltation is suggested to be a major contributor to the post-fire transport of medium to large charcoal particles. Particles lifted by the wind (probably no more than one metre above the ground) are deposited nearby perhaps disturbing other particles on impact and causing their temporary suspension (Clark, 1988a).

The above model provides a relatively comprehensive treatment of dispersal processes both during and after fires. It also introduces the processes of post-fire dispersal which are seldom addressed elsewhere.

**2.3.4 Pollen dispersal models and their implications for charcoal taphonomy**

The field experiments and theoretical models of charcoal particle dispersal provide some insight into the taphonomy of microscopic charcoal particulates. However, much greater understanding of the processes involved is needed to enable full interpretation of sediment records. The taphonomy of pollen grains has received a much greater quantity of research than charcoal taphonomy and because of the similarities in the processes of dispersal, deposition and sedimentation (Odgaard, 1992) theories of pollen taphonomy may be used to inform charcoal analysts. A number of the main theoretical treatments of pollen taphonomy are presented below and discussed in the context of their relevance to charcoal taphonomy.

*Tauber model (1965, 1977)*

The Tauber model is a schematic treatment of pollen dispersal in forested regions (Tauber, 1965, 1977). The basic concepts of the model have been widely accepted and have formed the basis for subsequent theoretical models (*e.g.* Jacobson & Bradshaw, 1981; Prentice, 1985, 1988). The basic tenet of the theory is that pollen assemblages in sedimentary basins are the sum of a number of components transported to the sediment from a range of distances, by a number of different physical processes. The theory is summarised by the following equation:

$$\mathbf{P} = \mathbf{C_g} + \mathbf{C_t} + \mathbf{C_c} + \mathbf{C_r} + \mathbf{C_w}$$

The total pollen sum (**P**) is composed of: pollen which falls directly into the lake from overhanging vegetation ($\mathbf{C_g}$) and thus has local origins; pollen carried to the lake through the trunk-space by low velocity winds ($\mathbf{C_t}$) and tends to be derived from vegetation within 100-1000 metres of the basin; pollen transported by turbulent winds immediately above the vegetation canopy ($\mathbf{C_c}$), such pollen could originate from plants growing up to tens of kilometres from the lake; pollen washed out of the atmosphere by rain ($\mathbf{C_r}$) which may have been transported great distances by high winds; and a pollen component washed into the lake by streams or surface runoff from the immediate catchment ($\mathbf{C_w}$) (Tauber, 1965; 1977).

The model provides a simple but effective means of outlining the contributions made by different transport mechanisms and the complexities involved in the formation of a sedimentary pollen assemblage. The importance of each mode of transport must be ascertained to gain a full appreciation of the pollen assemblage. The relative importance of each of the components is the subject of much disagreement, for example Prentice (1985, 1988) assumes the canopy component ($\mathbf{C_c}$) to be of primary importance whilst Bennett (1983, 1986) believes the water borne component ($\mathbf{C_w}$) to be predominant. It is clear that sites with different characteristics and from different environments may have very different charcoal inputs, each site should be considered on an individual basis, *e.g.* waterborne transport may be important in catchments with permanent inflow streams, high watershed area:lake area ratios and steep slopes (Jackson, 1994).

In terms of charcoal dispersal the basic concepts of the model are very useful. A number of different transport mechanisms, with a range of source areas, contribute to sedimentary charcoal assemblages, and the modes of transport are likely to be similar to those outlined for pollen. The determination of the relative importance of, and quantification of the contribution made by, each mode of dispersal is the key to understanding and interpreting the charcoal record successfully.

*Jacobson & Bradshaw 'basin size' model (1981)*

Jacobson & Bradshaw (1981) developed and modified the basic constructs of the model outlined by Tauber (1965; 1977). Their principal conclusions concern the relationship between sedimentary basin size and pollen source area: pollen source area increases as basin surface area increases; in basins with surface areas less that one hectare the dominant component of the pollen assemblage originates from within a few hundred metres of the basin; and for large basins, e.g. in excess of 75 hectares, the vast majority of the pollen comes from regional sources derived from the canopy ($C_c$) and 'rainout' ($C_r$) components (Tauber, 1965; 1977; Jacobson & Bradshaw, 1981).

Studies conducted by Bradshaw & Webb (1985) and Jackson (1990), which sought to estimate pollen source areas and compared them with basin size, confirmed the general validity of the model.

The basic principles of this model can also be applied to microscopic charcoal. Large lakes and bogs have the potential to trap charcoal from much greater source areas than small ones. As a consequence the influences of basin size should be considered when choosing sites for study, small basins or hollows should be used for studies of local fire activity and sediment records from larger lakes should be used for reconstruction of catchment wide or regional fire regimes (Jacobson & Bradshaw, 1981; Sugita, 1993; 1994; Bradshaw, 1994).

*Prentice model (1985, 1988)*

The Prentice model (Prentice, 1985; 1988) predicts the proportions of different pollen taxa deposited in a basin as a function of their deposition velocity (size and mass dependent), above-canopy wind velocity and basin radius. The model assumes that the dominant mode of pollen transport is by winds above the vegetation canopy, and that patterns of pollen dispersal conform to a leptokurtic curve (Prentice, 1985; 1988). Under constant wind speeds pollen source area increases with lake size and decreasing settling velocity of particles. As lake size and pollen source area increase the 'pollen rain' sedimented at a site becomes more homogeneous because it is increasingly well mixed in both the atmosphere and the lake basin before final sedimentation. This is reflected in the sedimentary pollen record by reduced resolution of local vegetation changes. Thus, the spatial scale of vegetation heterogeneity interacts with lake size, i.e. when a lake is substantially larger than the patch size of plant species in the landscape, pollen loading processes are likely to record vegetation as homogeneous rather than patchy (Prentice, 1985; Sugita, 1993; 1994).

Jackson (1994) describes the Prentice model as 'the best available model for estimating pollen source areas for basins where atmospheric transport is dominant'. The model produces results consistent with the majority of empirical studies of pollen source area (Prentice, 1985, 1988; Bradshaw & Webb, 1985; Prentice *et al.*, 1987; Gaudreau *et al.*, 1989; Jackson, 1990, 1991), correctly predicting the effects of basin size on pollen assemblages. Further comprehensive tests of its parameters are, however, still needed (Jackson, 1994).

The model elucidates a number concepts which can be applied to charcoal analyses: firstly, that charcoal source areas can be expected to increase with increasing basin size; secondly, that source areas are greater for smaller charcoal particles than for larger ones because of their lower settling velocities; and thirdly, that sedimentary charcoal records from large lakes will not necessarily be able to distinguish periods during which large numbers of small scale fires occurred in the catchment from periods in which a few large fires predominated (Prentice, 1985; 1988). The final concept is particularly applicable to moorland environments in which muirburn is practised for management purposes but occasional large scale uncontrolled fires occur (Imeson, 1971; Muirburn Working Party, 1977; Maltby, 1980).

*Prentice-Sugita model (1993, 1994)*

A modification of the Prentice model (1985, 1988) by Sugita (1993, 1994) to estimate pollen source areas for entire lake surfaces rather than just the point at the centre of the basin. The Prentice-Sugita model is more appropriate for approximating the source area of pollen in lake sediment, because mixing and focusing of sediment redistribute the pollen originally deposited over the entire surface (Davis, 1968; 1978; Davis & Brubaker, 1973; Lehman, 1975; Likens & Davis, 1975; Davis *et al.*, 1984; Jackson, 1994). The Prentice model is, however, still perhaps more appropriate for bogs and mires where horizontal and vertical movement of pollen after deposition is negligible (Clymo, 1973; Sugita, 1993).

The Prentice-Sugita model is based upon the same basic assumption as the Prentice model, *i.e.* that wind above the canopy and gravity below the canopy are assumed to be the dominant transport mechanisms. Pollen abundance is treated as a distance-weighted record of plant abundance, i.e. a tree 100 m away is represented by fewer pollen grains than a similar tree 10 m away.

Sugita (1993; 1994) made empirical predictions of pollen source area for a range of lakes with different diameters, using simulated landscapes of patchy vegetation. He found that: in general terms pollen source radii for entire basin surfaces were 10-30% smaller than those estimated by the Prentice model for a point at the basin centre; differences in source radius were also more profound for heavier pollen types; and average inputs to the entire surface were more strongly influenced by nearby pollen sources than pollen deposition at the centre. The pollen record from a lake may, therefore, have significantly different spatial resolution from that recorded by a bog of similar radius (Sugita, 1993; 1994).

'Relevant' source areas for pollen, the areas within which the pollen produced dominates the sediment assemblage, in simulated landscapes were within 50-100 m from the edge of forest hollows (radius = 2 m), 300-400 m for small lakes (radius = 50 m) and 600-800 m for medium sized lakes (radius = 250 m). Although only about 30-45% of the total pollen loading comes from within these distances, the model demonstrated that when background pollen was constant, this proportion was adequate to reflect local vegetation composition (Sugita, 1994).

Sugita's results also demonstrate how larger basin radii reduce site-to-site variations in pollen loading and the representation of pollen proportion. Large variations in pollen loading and proportion among small forest hollows (R = 2 m) result from strong pollen signals of localised source plants. Large lakes, however, have little or no site-to-site variation, indicating that pollen loading in large lakes records the spatial distribution pattern as homogeneous, rather than patchy (Sugita, 1994).

The Prentice-Sugita model has important implications for charcoal analysis. In terms of charcoal source areas the model suggests that local fires may have a far greater influence upon the sedimentary record than previously believed, because 'relevant' source areas of charcoal particulates may be rather smaller than previously estimated, especially for lakes. The results also reinforce the concept that larger particles are less mobile than smaller ones (Sugita, 1993; 1994).

### 2.4 The deposition and sedimentation of microscopic charcoal particles

Microscopic charcoal particles may be deposited, remobilised and redistributed many times before finally being incorporated into a sedimentary sequence (Patterson *et al.*, 1987). A factor which must be considered if charcoal records are to be interpreted effectively and accurately.

The majority of charcoal produced by a fire is, however, likely to remain within the boundaries of the parent fire (Clark, 1983), in the forms of partially charred plants still rooted in the ground, macroscopic fragments too large to be readily transported, and microscopic particles which have either not been lofted and dispersed by the fire or which were entrained temporarily in the atmosphere but deposited back within the confines of the fires limits. A large proportion of this charcoal deposited *in situ* will remain there, trapped within the micro-topographical features of the ground surface, until integrated into the sediment matrix. The proportion of the charcoal produced and dispersed widely at the time of the fire is likely to be relatively small (Clark, 1988a; Patterson *et al.*, 1987).

The ground surface on which charcoal particles are deposited determines whether they are susceptible to further transport. Particles falling onto bare unvegetated ground, especially in exposed locations or on steep slopes, are particularly susceptible to secondary transport by either aeolian or fluvial forces. Those deposited in live or partially charred vegetation are much less readily entrained and dispersed by wind or water, because even relatively sparse vegetation cover greatly reduces surface wind speeds (Gregory, 1945; Chamberlain, 1975) and moderate amounts of leaf litter greatly reduce the effectiveness of overland air and water flows to remove particulates from the soil surface (McVean & Lockie, 1969). Moist land or plant surfaces have extremely high retention capacities and are effective at preventing further mobilisation of small particulates.

Water bodies act as perfect sinks for microscopic particulates, once trapped by the surface tension of the water the retention capacity is so great that they will not be returned to the atmosphere by even the strongest winds (Green & Lane, 1964). However, charcoal particles deposited in streams or lakes can be susceptible to a number of complex redistribution and sedimentation mechanisms both within and between sedimentary basins (Davis, 1968; 1973; 1978; Davis & Brubaker, 1973; Davis *et al.*, 1984; Lehman, 1975; Likens & Davis, 1975).

Charcoal analyses are normally conducted on three main types of sedimentary matrices, soils, peats and lacustrine sediments. Each have unique characteristics and problems as depositional environments, these shall now be discussed. The processes of deposition and sedimentation of microscopic particulates in lakes are much more complex than for soils and peats and therefore receive more attention.

### 2.4.1 Soils

The number of charcoal analyses conducted on soil profiles has been limited (*e.g.* Iversen, 1941, 1969). Possibly because charcoal analyses are generally conducted as adjuncts to pollen analyses and pollen studies on soils are rare (Dimbleby, 1981). Soils are seldom used for pollen analyses because the anoxic conditions necessary to preserve pollen are rarely found and consequently the pollen are generally degraded and difficult to identify. Soils also accumulate much more slowly than peats and lake sediments and therefore provide relatively low resolution palaeoenvironmental records (Dimbleby, 1961; 1985; Bradshaw, 1994). An exception to these general rules are forest mor humus soils which have provided a number of high quality pollen and charcoal records (*e.g.* Iversen, 1969; Bradshaw & Zackrisson, 1990; Bradshaw & Hannon, 1992). Whilst problems of low accumulation rate and resolution are shared by charcoal analyses of soils, charcoal preservation is much less problematic because it is chemically inert (Goldberg, 1985). Charcoal analyses of soils, therefore, are potentially useful for reconstructing fire histories in a wide range of environments.

The movement of charcoal particles following initial deposition on a soil surface is controlled by a complicated interaction of factors, the most important being: vegetation type and density, micro-topography of the soil surface, moisture content of the soil surface, slope gradient, soil structure and hydrology, and local climate (principally wind speeds and direction, and rainfall intensity). Due to the slow accumulation rates particles may remain on the soil surface exposed to agents of dispersal for protracted periods of time before incorporation and final stabilisation (Griffin & Goldberg, 1975; Clark, 1983).

Charcoal deposited on bare ground is more likely to experience secondary distribution than that falling beneath vegetation (Chamberlain, 1975). Particles deposited on rough soil surfaces, composed of larger aggregates and broken by obstacles such as rocks, are less susceptible to wind erosion than those on relatively flat and uniform surfaces. Soil surfaces with high moisture contents will have high retention capacities for small particles, retaining them within the surface tension of soil water. Charcoal particles on dry soils are much more susceptible to redistribution by surface winds. On steep slopes gravity enhances particle movement in a down-slope direction and retards up-slope movement. Soils with high infiltration capacities, common in humus rich forest and moorland soils, are only subject to surface runoff under extreme precipitation conditions and thus particulates deposited on them are unlikely to experience transport by such mechanisms (Waring & Schlesinger, 1985). Similarly, particle movement is likely to be greatest in regions where agents of dispersal are strongest, *i.e.* those areas with strong winds and high rainfall (Bagnold, 1941; Chepil, 1945).

The deposition of particles onto vegetation involves a complex interaction of gravity and impaction processes (Chamberlain, 1975). Many particles < 5 μm in length are retained on plant surfaces after initial impacts, especially those surfaces which are wet, sticky or hairy, and once at rest they are not easily disturbed by wind alone because surface tension and other forces hold them, and the drag of the wind is reduced by the viscous sub-layer (Gregory, 1961; Chamberlain, 1967a; Chadwick, 1972). Most are probably washed off the plants and deposited on the ground beneath by rainsplash mechanisms, although a small proportion may be liberated and re-dispersed. On impact with plant surfaces larger particles are more likely to rebound from surface to surface by saltation, or to be retained temporarily and then subsequently removed, soon becoming resident on the ground surface below the canopy (Chamberlain, 1975). Once the particulates are on the soil surface below the vegetation they will rarely be moved by the wind because the shearing stress on the soil is too low even in high winds (Chamberlain, 1975).

After incorporation into the soil matrix the movement of particles is likely to be variable and dependent upon a number of factors. Dimbleby (1985) suggests that in some instances pollen, and presumably other microscopic particulates such as charcoal, can be locked in humic complexes in the soil preventing movement. However, in other instances significant down profile movements of particulates may occur in water percolating through the soil (Dimbleby, 1985), although other studies have dismissed such movements as being insignificant (Havinga, 1974). Movements of microscopic particulates in soil matrices may also be facilitated by soil fauna. In some well aerated soils rich in fauna, vertical and lateral movements of particles may be considerable (Walch *et al.*, 1970; Dimbleby, 1985; Andersen, 1986). In acid soils, such as moorland podzols and mor humus rich soils, mixing is minimal because earthworms and other fauna are absent (Dimbleby, 1985). Soils subjected to minimal faunal mixing and percolation disturbance can be reasonably well stratified and provide clearly defined charcoal records, and even those which have experienced some disturbance can yield useful information if interpreted with care (Dimbleby, 1956, 1985; Moore *et al.*, 1991).

### 2.4.2 Peats

Charcoal particles deposited on peats are subject to possible processes of subsequent transport similar to those encountered on soil surfaces. When the ground surface is bare the particles are more susceptible to remobilisation than when it is covered by vegetation or plant debris. In addition, the predominantly wet nature of bog surfaces impede particulate movement. A number of authors have commented that once deposited on a vegetated bog surface pollen and charcoal are highly unlikely to be redistributed (Gillette & Goodwin, 1974; Chamberlain, 1975).

Following incorporation in the peat matrix vertical movement of particles within bog profiles is likely to be minimal and generally unimportant on the time scales usually encountered in palaeoecological studies (Birks & Birks, 1980). This does not, however, rule out movement at very fine scales, as small-scale movements due to changing levels of the water table can occur (Clymo, 1973). However, studies using finely sampled peats have shown large sample-to-sample variations in pollen abundance which correlate well with environmental characters and suggest post-depositional stability (*e.g.* Green *et al.*, 1988; Polach & Singh, 1980). Peats generally provide sedimentary sequences of considerably higher resolution than soils, although rates of peat accumulation can vary markedly over time, both within and between individual bogs (Clymo, 1973).

### 2.4.3 Lakes

Lake sediments are the most commonly used sedimentary medium for charcoal analyses, however, they are also the most complex of the depositional environments encountered. The processes controlling the sedimentation of microscopic particulates from their initial deposition on the lake surface to final incorporation in the sedimentary sequence are potentially complicated, highly variable and by no means fully understood. The processes of differential deposition, redeposition and focusing (Davis, 1968; 1973; 1978; Davis & Brubaker, 1973; Davis *et al.*, 1984; Lehman, 1975; Likens & Davis, 1975) have important implications for understanding and interpreting sedimentary microfossil records. The majority of theoretical and experimental work discussed below refers to the sedimentation of pollen, however, the fundamental principles are generally applicable to (Davis & Brubaker, 1973), and have been adopted by charcoal analysts (Patterson *et al.*, 1987; Odgaard, 1993; Scott & Jones, 1994).

Within the first few days of entering a lake differential sedimentation of different sized particulates may result in variations in the spatial distribution of particles over the bottom of lake basins. Differential sedimentation was first outlined by Davis & Brubaker

(1973) using submerged pollen traps in Frains Lake, Michigan. Ragweed pollen, because of their small size and low mass, were found to have sufficiently slow sink rates that they were swept across the lake by wind-driven currents before sinking to depth in the water column. The initial input of ragweed pollen was, therefore, predominant in the littoral sediment on the windward side of the lake. In contrast, larger oak pollen were deposited more or less equally throughout the lake because the wind-driven water currents failed to significantly affect their deposition (Davis & Brubaker, 1973).

Similar mechanisms are likely to influence the initial settling of microscopic charcoal particles. An appreciation of the differences in settling behaviour between charcoal particles and pollen has been gained through a number of theoretical and experimental studies (Skolnick, 1958; Davis, 1967; Renfrew, 1973; Cope, 1984; Odgaard, 1993). Renfrew (1973) estimated the specific weight of charcoal to be between 1.4-1.7, approximately equal to that for pollen exines, 1.4-1.5 (Flenley, 1970). However, the porous nature of charcoal particles (60-80%; Renfrew, 1973) may greatly reduce the apparent specific gravity of charcoal to between 0.3-0.6 (Patterson *et al.*, 1987). Such low specific weights and the small size of the majority of particles in lake sediments (55% are between 82-172 $\mu m^2$) suggest that settling rates of charcoal particles in water are likely to be lower than those of angiosperm pollen (Patterson *et al.*, 1987).

Laboratory experiments to determine rates of charcoal settling through water columns have provided contradictory results. Skolnick (1958) experimented with the deposition times of a range of different sized charcoal particles (significantly larger than those commonly found in lacustrine sediments) in a water bath. He observed that unlike typical inorganic clasts, which tend to settle out of the transporting medium as soon as competency falls below the critical threshold velocity, charcoal fragments remain afloat for long periods of time (the time periods are not noted) until they become waterlogged (Skolnick, 1958). Cope (1984) obtained similar results, he observed the depositional behaviour of four size classes of *Pinus* charcoal fragments (1-2, 2-4, 4-8 & 7-8 mm length) in an agitated water bath over a period of seven months. Progressively larger particles remained afloat for longer, some remaining afloat after seven months. Davis

(1967) mixed small charcoal fragments, similar in size to those encountered in lake sediment cores, with water and found that they soon became saturated and sank.

Although the differences in the sizes of charcoal particles complicate the comparison of the results from these experiments, a key concept common to them all is that charcoal particles, regardless of size, need to be waterlogged before settling through the water column. The implications of this are that charcoal particles will be deposited most rapidly under agitated water conditions which generally facilitate rapid waterlogging. Under still water conditions, rarely encountered in natural water bodies, charcoal particles may be dispersed and deposited widely, the larger ones (which take longer to become waterlogged) being deposited in the windward margins whilst the very small ones are deposited more evenly over the basin sediments. Such processes also have implications for the differential loss of particles from lake systems with significant outflows. Large buoyant particles are most likely to be lost via the outlet, altering the input-sedimentation equation and complicating the interpretation of the sedimentary record (Davis & Brubaker, 1973). A further implication is that dry charcoal particles entering a lake from the atmosphere will settle more slowly than those transported to the lake in stream courses and which are already saturated. Further work needs to be done on all aspects of charcoal deposition to elucidate questions such as the magnitude in differences in specific gravity of charcoals produced at different temperatures and the implications for their dispersal and deposition (Scott & Jones, 1994).

Initial deposition of a particulate on the lake floor may be followed by a protracted period of resuspension and redistribution before final incorporation into the sedimentary sequence occurs (Davis, 1968; 1973; 1978; Davis & Brubaker, 1973; Davis *et al.*, 1984; Lehman, 1975; Likens & Davis, 1975; Odgaard, 1993). Pioneering work in this field was carried out by R.B. Davis (1967) who noted the effects of sediment mixing on lacustrine charcoal records. Davis observed that charcoal peaks in a sediment core produced by severe local forest fires were relatively insignificant and indistinct despite the fact that high winds during, and rainfall events soon after the fires ensured that great quantities of charcoal were rapidly transported to the lake (Davis, 1967). The vegetation around the lake re-established itself quickly and small quantities of charcoal were visible on the land surface a couple of years after the fires suggesting that most of the charcoal had entered the lake in a short period of time. Why were the charcoal peaks not more prominent? In order to establish that the charcoal had not been floating on the lake surface for many years before deposition Davis mixed charcoal particles of a similar size to those found in the lake sediments in a water bath in the laboratory and found that they soon sank. He concluded that the vertical spread in the charcoal peaks (over more than 20 years' sediment depth) must be due to the mixing of sediment after initial deposition (Davis, 1967).

Studies have illustrated that lacustrine sediments can be mixed by burrowing organisms, annual over-turn events or wind-induced currents (Davis, 1967; 1974). The effects of burrowing fauna, such as tubificids, and seasonal over-turn can be important in a restricted number of cases, however, the effect of wind-induced currents are far more important in a greater number of cases (Davis, 1968; 1973; 1978; Davis & Brubaker, 1973; Davis *et al.*, 1984; Lehman, 1975; Likens & Davis, 1975; Jackson, 1991). The majority of studies of sediment mixing and redeposition in lakes have been pollen based (Davis, 1968; 1973; 1978; Davis & Brubaker, 1973; Davis *et al.*, 1984; Lehman, 1975; Likens & Davis, 1975; Jackson, 1991). Davis (1968) was the first to quantify the general movement of pollen and sediment from shallow littoral zones to deeper basins within lakes by wind induced currents. She found that sediments resuspended in shallow areas were mixed in the surrounding water and redeposited over the whole of the basin, repeated resuspensions resulted in net accretions of sediment in the deeper areas. Subsequent studies have reinforced these theories (Jackson, 1994). It has been estimated that pollen grains (and presumably other microscopic particulates) are deposited on average two to four times before being buried deeply enough to escape further resuspension and redeposition (Davis, 1978). In extreme cases, however, in particularly exposed locations such as the western seaboard of Scotland, wind-induced currents in lakes can prevent sediment coming to rest in water depths in excess of 50-60 m and many resuspensions may occur (Pennington *et al.*, 1972).

Redeposition processes redistribute sediment without sorting, *i.e.* organic and inorganic material (except large sand grains) are moved together with no evidence of differential settling related to particle size or weight (Davis, 1973). However, processes of redeposition do alter initial patterns of particle distribution. The movement of sediment rich in smaller pollen, initially deposited in the shallow lake fringes, to the basin centre tends to equalise the absolute amounts of smaller pollen over the basin (Davis & Brubaker, 1973). In contrast resuspension and deposition of shallow but not deep water sediments concentrates the larger pollen, which were initially deposited evenly over the lake floor, in the deeper basins (Davis, 1973). Consequently, the ratio of small:large pollen is highest in the shallower areas than the deeper ones. Sediment focusing in lakes has been indicated in a number of pollen accumulation studies by continuous up-core decreases of pollen sedimentation rates as the lakes fill in (Lehman, 1975; Odgaard, 1993). The effects of sediment focusing are further complicated by the effects of sediment compaction with depth. To account for the combined effects of these problems and to aid interpretation of sediment charcoal profiles Odgaard (1993) built a regression factor into his model of charcoal deposition, an approach which may be of value in subsequent studies.

Redeposition processes mix new sediment with older previously deposited sediment and, therefore, tend to 'smooth' temporal variations in sediment input (Davis, 1973). Green (1981) observed that sediment mixing acts like a 'moving average process', observed charcoal values in sediment samples for a certain time effectively equate to weighted means of actual charcoal inputs for periods spanning several years both before and after initial deposition. Davis *et al.* (1984), Davis (1978) and Jacobson & Bradshaw (1981) all found evidence of significant pollen and sediment mixing and state that a moderate amount of sediment mixing is not necessarily detrimental to the reconstruction of vegetation records, on the contrary in many cases the 'smoothing' of pollen records can be advantageous. Moderate mixing imparts a degree of uniformity and consistency to sedimentary pollen contents (Davis, 1978), integrating annual differences in pollen production that might otherwise complicate analyses of vegetation composition (Jacobson & Bradshaw, 1981), although obviously, excessive amounts of mixing will obscure fine resolution changes.

In terms of charcoal analyses the process of mixing may have greater detrimental implications. Charcoal is generally produced by very short duration fire events and is generally deposited perhaps more rapidly than pollen (Clark, 1983). Theoretically in the sediment record of a 'perfect sink' (in which rapid deposition with no mixing or redeposition occurs) fire events would be represented by discrete, individual charcoal layers bounded by sediments devoid of charcoal (representing fire free periods). Redeposition and mixing processes, however, destroy the individuality of each fire event, rendering sedimentary sequences from well mixed lacustrine sediments useful only for determining and defining periods of relative fire abundance and surfeit in a catchment.

In studies of lake sediments multiple core approaches are preferable to single core records because they provide an insight into changing depositional regimes (Edwards & MacDonald, 1991). Palaeoecologists, however, tend to collect a single core from the deepest point in a lake basin, because of the labour intensive nature of palynological investigation. Davis *et al.* (1984) conclude that where single cores are used the deepest point is probably the best location to use. The deepest point is often the area experiencing the most rapid rate of deposition, as the focal point of sediment focusing (although it might not have been so in the past), and thus resolution is greatest. The sediment record in the deepest part of a lake is also most likely to be most complete (free from uncomformities and hiati) as it is the area of the lake most sheltered from wind-driven water currents (Davis *et al.*, 1984). Only complete sequences of annually laminated sediments from deep sedimentary basins, where the effects of mixing can be discounted, can be taken to provide undisturbed, high resolution environmental records (Saarnisto, 1986; Clark, 1988b). All other sediment sequences should be treated with caution and interpreted with care.

Processes of deposition, resuspension, redeposition and focusing vary greatly from lake to lake, the principal controls being basin morphometry and the strength of local wind driven currents (Odgaard, 1993). Unfortunately there is no means of assessing which lakes have fewest problems before sampling (Sarmaja-Korjonen, 1992). The effects of sediment focusing, when significant, need to be accounted for during profile interpretation (See section 2.8.4).

### 2.5 Site selection

The selection of a site for charcoal analyses follows the same general principles defined for palaeovegetation studies (Jacobson & Bradshaw, 1981). The characteristics of the site selected determine the type of application to which the individual site is suited, and the detail and reliability of the inferred reconstructions (Bradshaw, 1994). Specific types of site can be chosen to answer pertinent research questions (Jacobson & Bradshaw, 1981), however, the wrong choice of site may greatly restrict the success of a project. The large amount of time required to collect and analyse palaeoecological data makes the consideration of suitable sites a major concern.

Study sites should be chosen on the basis of the aims of the research problem to be addressed, the temporal and spatial scales to be studied, and the availability of a suitable sediment deposit in the proposed study area. Lake sediments, peats and soils can all be used for microscopic charcoal analyses. The type of deposit sampled, the size and topographic characteristics of the depositional basin and the prevailing taphonomic processes at the site all have important implications for the fire history reconstructed.

#### 2.5.1 Lakes

Lake size, basin morphology, catchment topography / geology / soils / vegetation / hydrology, microclimatology, and sediment characteristics vary greatly and as a consequence so do their charcoal source areas and possible applications of the sediment record for fire history reconstruction (Sarmaja-Korjonen, 1992). Perhaps the most important characteristic controlling the nature of the charcoal record 'sensed' by a lake is its size (Jacobson & Bradshaw, 1981; Bradshaw & Webb, 1985). Large lakes tend to receive charcoal from large, predominantly regional source areas and are preferred for studies of regional fire history (Tolonen, 1983; Edwards, 1987). Progressively smaller lakes trap predominantly locally produced charcoal and are suited to reconstructions of more local fire histories (Jacobson & Bradshaw, 1981; Bradshaw, 1994).

The characteristics of lakes and their catchments also determine the major processes by which the charcoal is transported to, and deposited in, the lake. The most appropriate lakes for reliable detection of atmospheric charcoal input have essentially closed, relatively shallow basins, without any major inflowing streams, very small outflows, very small drainage areas, gentle shores and ideally, dense wetland vegetation around their perimeters to effectively filter the long-term input of charcoal particles transported by surface runoff. Ideal lakes to collect charcoal from surface runoff would be small, closed, and deep, with steep surrounding slopes and without a wide filtering vegetation zone on the shore (Terasmae & Weeks, 1979; Tolonen, 1983).

The potential of lake sediments for the reconstruction of highly temporally resolved records depends upon the degree of sediment mixing and redeposition experienced on the lake floor. Only annually laminated lacustrine sediments can be relied upon to provide high precision records, all other sediment sequences must be treated as if at least some mixing may have occurred (Saarnisto, 1986).

### 2.5.2 Peats

Peat deposits generally provide less useful information about regional fire histories than lake sediments because they recruit charcoal from much more local source areas (Tolonen, 1983; Edwards, 1987). Bog surfaces do receive inputs of charcoal from regional sources ('background' deposition) but the quantities are generally so small that they are relatively insignificant when diluted by the dominant local component (Sugita, 1994).

The processes of charcoal particle dispersal and sedimentation in peatlands are significantly different, and generally less complex, than those at lake sites (Bradshaw, 1994). The inputs of microscopic charcoal to peats are likely to be similar to those for pollen. The major inputs being from atmospheric sources (Green & Dolman, 1988; Bradshaw, 1994), although waterborne components cannot be totally discounted, particularly in rheotrophic mires (Moore *et al.*, 1991). As is the case with lake sites the topographic characteristics of the mire or bog determine the nature of the source area from which charcoal is recruited, i.e. small enclosed hollows generally record more local histories of fire than larger, more open peatlands (Patterson *et al.*, 1987; Sugita, 1994).

Stratified peat deposits are particularly useful for high resolution fire histories because post depositional, horizontal and vertical mixing of microscopic particulates is generally minimal (Clymo, 1973). In some cases palynomorphs may experience movement but the influence on the stratigraphic record is likely to be insignificant (Clymo & Mackay, 1987). Turner & Peglar (1988) and Green *et al.* (1988) conducted extremely fine resolution palynological studies of peat deposits and evidence of mixing was undetected.

Peatlands are generally wet and thus rarely burn, although their drier margins may be more susceptible to fire (Tolonen, 1983). When they do burn, however, the fire events are recorded by conspicuous charcoal layers within the peat stratigraphy (Tolonen, 1983; Edwards, 1987). *In situ* fire events are, therefore, generally readily identifiable in comparison with local or extra-local fire activity.

### 2.5.3 Soils

Soils, like peats, generally provide records of local fire activity, as although they may receive some input of charcoal particulates from extra-local or regional sources it is insignificant in comparison with that produced by local fires (Patterson *et al.*, 1987; Sugita, 1994). Charcoal records from soil profiles should not, therefore, be interpreted in terms of regional fire activity. Indeed, data provided in Chapters 4 and 5 of this thesis suggest that soil core charcoal records are perhaps only relevant for reconstructing *in situ* fire activity. In moorland soils the dominant sources of charcoal are most likely to be *in situ* fires (Rhodes, 1995) or atmosphere inputs during or immediately after local fires. Some dispersal of charcoal in overland water flows may occur but this is likely to be of minimal importance in most cases (Clark, 1991).

Well stratified soils with a high degree of temporal integrity, *i.e.* those which have not experienced extensive mixing, erosion and loss of soil material, or deposition and addition of non-contemporaneous material, are of most use to the charcoal analyst. Acidic soils, such as podzols, in which faunal life is restricted provide perhaps the best opportunities for finding relatively undisturbed soil profiles (Dimbleby, 1985). A number of studies have produced good palaeoenvironmental charcoal records from forest and moorland podzols and mor humus soils, *e.g.* Iversen (1941, 1969), Whittington (1983), Odgaard (1988), Bradshaw & Zackrisson (1990), Mitchell (1990), and Bradshaw (1993).

In order to find continuous, relatively undisturbed soil profiles it is best to avoid locations on steep slopes which may have experienced erosion, or at the base of slopes where colluvial material may be deposited. Flat, uniform ground surfaces perhaps provide the best opportunities for good soil profiles, but if they are not available water-shedding locations are preferable to ones receiving flows of surface water which could carry re-worked sediments and charcoal.

**2.6 Sampling**

The issue of sediment sampling strategies and their implications for the interpretation of charcoal profiles have been addressed in detail (R.L. Clark, 1983; 1987; J.S. Clark, 1988; Green & Dolman, 1988). Clark (1983; 1987) was the first to address the matter in a systematic manner providing a theoretical model of how sampling regimes of different intensities alter the form and resolution of a sedimentary charcoal profile and the amount of information to be gained from it. The subsequent studies of Clark (1988) and Green & Dolman (1988) reiterate the same fundamental concepts.

A principal problem is the conflict of scales between the relatively slow accumulation rates of sediments and the short duration of fire events. Vegetation fires are short duration events, lasting from several hours to a maximum of several weeks. In theory, given rapid charcoal dispersal and deposition, limited delayed transport of charcoal from the catchment to the sediment sink, and minimal post-depositional disturbance, local fires should be represented in sediments as discrete horizons of microscopic charcoal of perhaps 1-2 mm in thickness. Problems of resolution arise, however, because typical sub-samples taken from cores for analysis are one centimetre thick, a depth of sediment which may represent between 5-20 years (or in many cases much longer periods) worth of deposition in a lake or bog (Clark, 1988). Much higher resolution sampling, 1-2 mm sediment slices, are required to 'sense' individual events effectively. Individual fires may be resolved in one centimetre thick sections of the sediment when fire recurrence intervals are greater than the time period contained in the sample, but when several fires occur within the period of a single sample the charcoal from the separate fires will be agglomerated. In practice, therefore, the amalgamation of charcoal from several fires is almost inevitable when dealing with such coarse sampling densities.

Matters are further complicated by the fact that in most lakes, even when very fine interval samples are taken (1-2 mm thick) the processes of mixing and redeposition combine the charcoal from a number of fires. The charcoal in an individual sediment sample may be the product of a single fire diluted by sediment from years of no fire, or the product of many fires within the period over which the sediment has accumulated (Clark, 1983; 1987; Clark, 1988). Varved sediments provide the only means of attaining a degree of temporal control (Saarnisto, 1986), however, even within the time taken for an individual lamination to form many fires may have burned within the catchment and the charcoal within the lamination may be the product of many of a number of these fires. In the sediment record it is impossible to distinguish between the microscopic charcoals produced by different fires.

The resolution of the record is obviously highest when sampling frequency is greatest and fine resolution samples are taken contiguously. Long sedimentary sequences, however, are rarely sampled contiguously, because time constraints on analyses dictate that in most cases samples are taken at minimum intervals of 4 or even 8 cm. Therefore, large gaps occur in the reconstructed fire record. Clark (1983; 1987) illustrates the extent to which a charcoal record can be distorted by different sampling intensities. Coarse sampling schemes miss much more fire activity than they record providing little more than cursory information about fire frequency, and allowing no more than gross generalisation of changing fire regimes over time.

Sampling strategies are also constrained by the nature of the sediment, the methods of core collection and the method of charcoal quantification. Unconsolidated lake mud and fibrous peat are much more difficult to section thinly than clay-rich or well humified sediments, an important consideration if high resolution records are required. Monoliths of peats and soils have proven particularly useful for capturing large sediment samples which can be sectioned accurately using a microtome (Turner, 1964). Freeze coring technologies have been at the centre of advances in high resolution palynology and charcoal analysis of annually laminated lacustrine sediments (Cwynar, 1978; Tolonen, 1978; Gajewski *et al.*, 1985; Clark, 1988; Green & Dolman, 1988; Peglar, 1993). Sample preparation and charcoal quantification techniques which allow the processing of large numbers of samples are necessary to produce high resolution fire histories, see section 2.7 for a treatment of possible methods.

**2.7 Sample preparation & counting procedures.**

In the five decades since the inception of microscopic charcoal analyses a great number of techniques have been devised (See reviews in Tolonen, 1986; Patterson *et al.*, 1987). Unlike in the field of palynology, where a small number of methods (Faegri & Iversen, 1989; Moore, Webb & Collinson, 1991) have been adopted universally, standard sample preparation and charcoal quantification procedures have not been accepted (Patterson *et al.*, 1987). Perhaps the principal reason for this is that different preparation and quantification methods are more practical and appropriate for specific studies, depending upon the aims of the analyst, the characteristics of the site and the sedimentary assemblage under scrutiny. For example, a petrographic thin section method would be more appropriate than a pollen slide point count method for reconstructing local fire activity from varved lake sediments (Clark, 1988; Clark *et al.*, 1989: Clark & Royall, 1995).

For this study a single preparation procedure and two different charcoal quantification strategies were used, one for the analysis of soil cores and one for lake sediments. To provide the rationale behind their adoption, the alternative methods used by previous exponents of charcoal analysis will be discussed.

The counting of charcoal on pollen slides has been, and still is, by far the most frequently used approach, accounting for 78% of the 156 studies noted here (See Appendix 1 for a full list). The principal reason being that the majority of charcoal analyses are conducted in conjunction with pollen studies and analysts can save both sample preparation and counting time by quantifying the pollen and charcoal simultaneously. Despite the acceptance of pollen slide preparations as a medium for charcoal quantification by the majority of analysts no single standard counting technique has achieved general acceptance. Broadly similar methodologies are practised but practically all authors slightly modify parameters such as the size ranges of particles counted, the number and form of size classes used, or how charcoal abundance is expressed. As a consequence a bewildering range of methodological considerations exist for prospective analysts.

In order to simplify matters greatly and allow a generalised discussion, the pollen slide charcoal techniques have been divided into four broad categories:

[1] *Absolute particle abundance methods* - all charcoal particles are counted regardless of size to provide a measure of the total number encountered on the slide (*e.g.* Iversen, 1941; Davis, 1967).

[2] *Size class methods* - individual charcoal particles are tallied into predetermined size classes, on the basis of particle length or surface area, using an eyepiece grid or graticule. Charcoal abundance can be expressed as an area of charcoal in each individual size class or as a total area of charcoal encountered in a sample by summing the areas of the individual size classes (*e.g.* Waddington, 1969; Swain, 1973).

[3] *Point count method* - charcoal abundance is quantified by recording the number of hits on charcoal particles scored by a standard number of points on an eyepiece reticle during scans of a predetermined area of slide (Clark, 1982).

[4] *Subjective estimate* - estimation of the charcoal content of a sample on either a 5/7-point scale or percentage basis (*e.g.* Tallis, 1975; Tolonen, 1983).

Table 2.1 provides a summary of the relative popularity of charcoal quantification methods within a sample of 156 charcoal studies (See Appendix 1 for a full list) performed during the past six decades. The pollen slide methods are also compared with alternative approaches.

Table 2.1: Temporal trends in the application of microscopic charcoal quantification methods.

| Charcoal Quantification Method | Time period (i.e. 40-49 = 1940-1949) 40-49 | 50-59 | 60-69 | 70-79 | 80-89 | 90-94 | Total |
|---|---|---|---|---|---|---|---|
| Pollen slide - Particle abundance | 1 | | 3 | 5 | 21 | 19 | 49 |
| Pollen slide - Size class / Particle area | | | 1 | 9 | 23 | 9 | 42 |
| Pollen slide - Point count | | | | | 15 | 12 | 27 |
| Pollen slide - Subjective estimate | | | | 1 | 2 | 1 | 4 |
| Chemical digestion / ignition / spectroscopy | | | | 4 | 9 | 1 | 14 |
| Petrographic thin sections | | | | | 3 | 2 | 5 |
| Petri dish | | | | | 1 | | 1 |
| Macrofossil | | | | | 4 | 10 | 14 |
| **Total** | 1 | | 4 | 19 | 78 | 54 | 156 |

Over the period from 1940-1994 the absolute abundance and size class methods have been most frequently employed, however, the point count method (Clark, 1982) has gained popularity more recently because of the speed at which samples can be processed. Subjective estimates of charcoal abundance on pollen slides are rarely used in favour of the more quantitative approaches, they can, however, be useful when sedimentary charcoal contents of samples are extremely high (Vuorela & Hiekkanen, 1991).

Table 2.2 summarises the relative merits and weaknesses of each of the techniques. Each individual method has a number of positive and negative characteristics and pollen slide methods as a whole have a number of common advantages and deficiencies. As mentioned previously a great benefit of pollen slide methods is that no additional sample preparation is necessary beyond the preparation of the pollen slides. In addition, all of the counting methods are relatively quick and easy, point counts and subjective estimations being more rapid than size class methods, and can be performed at the same time as pollen counts.

Table 2.2: The merits and weaknesses of pollen slide charcoal analysis techniques.

| Method | Positive points | Negative points |
|---|---|---|
| **Pollen slide - absolute abundance** | 1. Utilises pollen slide preparations<br>2. Counting relatively quick & easy | 1. Particle fragmentation & loss during preparation<br>2. Large particles 'sieved-out' during slide preparation<br>3. Uncertainty of identification<br>4. No account for particle size |
| **Pollen slide - size class** | 1. Utilises pollen slide preparations<br>2. 'Local vs regional' source determination using size classes | 1. Particle fragmentation & loss during preparation<br>2. Large particles 'sieved-out' during slide preparation<br>3. Uncertainty of identification<br>4. Measurement of particles time consuming |
| **Pollen slide - point count** | 1. Utilises pollen slide preparations<br>2. Counting very quick & easy | 1. Particle fragmentation & loss during preparation<br>2. Large particles 'sieved-out'<br>3. Uncertainty of identification<br>4. No account for particle size |
| **Pollen slide - subjective estimate** | 1. Utilises pollen slide preparations<br>2. Extremely quick & easy | 1. Particle fragmentation & loss during preparation<br>2. Large particles 'sieved-out' during slide preparation<br>3. Uncertainty of identification<br>4. No account for particle size<br>5. 'Subjective' estimation error |

The main disadvantages of pollen slide techniques are several fold. Perhaps most important is the detrimental effect that preparation procedures have on charcoal particles. Pollen slide preparation procedures are both chemically and mechanically rigorous (Faegri & Iversen, 1989; Moore, Webb & Collinson, 1991), this is necessary in order to digest and remove organic and inorganic material from the sediment matrix. Pollen grains are highly resistant to the preparation processes because of their sporopollenin rich exines

(Birks & Birks, 1980) and generally survive them in tact and undamaged. Fossil microscopic charcoal particles, however, are much less robust. Although carbon is chemically inert (Clark, 1984; Scott & Jones, 1991) charcoals produced by biomass burning are rarely composed of pure carbon (Goldberg, 1985) and so they are susceptible to oxidation and degradation during acetolysis. Perhaps more importantly, charcoals are mechanically fragile, especially when saturated, and thus sieving, stirring and particularly centrifuging of samples will cause particle fragmentation. Clark (1983; 1984) proved the significant extent to which pollen preparation procedures cause charcoal fragmentation and loss, and it is for this reason that such preparation techniques are far from ideal. Every precaution should be taken to preserve the form of the original sedimentary charcoal population during sample processing, minimising particle fragmentation and loss and thus ensuring that the charcoal index reconstructed provides a true representation of that deposited and sampled.

Sediment samples processed by standard pollen preparation procedures are normally passed through *circa* 180 micron aperture sieves to remove unwanted detrital material (Moore *et al.*, 1991), however, large charcoal particles are also removed. The consequences of this process must be taken into consideration when quantifying charcoal on pollen slides and approaches count particles into size classes are rendered particularly impotent. The removal of larger particles, and particle fragmentation, results in over 90 percent of the charcoal found on pollen slides being between 5 and 20 µm in length (Patterson *et al.*, 1987). Such small particles behave like dust in the atmosphere, having the potential for being transported great distances before being deposited. Pollen slide charcoal assemblages, therefore, tend to provide records of regional fire activity unless sites are carefully selected to provide a more local record (See Section 2.5). A number of authors have sought to redress this problem by saving the sieve washings, quantifying the charcoal in them and using the charcoal counts in conjunction with the pollen slide counts (Mehringer *et al.*, 1977; Robinson, 1987; Bradshaw, 1993).

Correctly identifying the charcoal represents a further fundamental problem associated with quantifying charcoal on pollen slides. Microscopic charcoal particles are by definition very small (predominantly 5-20 µm in length, Patterson *et al.*, 1987), and even under x400-500 magnification (typically used for pollen analysis) structural features necessary for conclusive identification are indiscernible or absent in most cases. Most analysts identify charcoal particles on the basis of being angular, uniformly black and opaque (Swain, 1978; Head, 1980; Battson & Cawker, 1983; Edney *et al.*, 1990; Clark *et al.*, 1989). Such identification criteria are highly questionable because they are fulfilled by other organic and inorganic particles found in pollen preparations, *e.g.* pyrite, marcasite and biotite (Bolton, 1988). Pollen processing procedures have also been found to darken organic material considerably (Clark, 1984) and this great care is needed in counting charcoal on pollen slides. Some authors have attempted to eradicate errors by making type slides of charcoal samples to aid in identification (*e.g.* Davis, 1967), however, unequivocal identification is still difficult.

It is evident that although pollen slide methods are the most widely used methods of charcoal analysis they are far from perfect, and as a consequence a range of alternative approaches have also been developed. Table 2.3 summarises the relative merits and weaknesses of the principal alternative methods.

Chemical digestion-assay methods were developed to quantify the elemental carbon content of sediments without having to perform tedious microscope counts (Tallis, 1975; White & Hannus, 1981; Griffin & Goldberg, 1983; Winkler, 1984). In theory such techniques should produce charcoal records unaffected by biases encountered by pollen slide methods. The percentage carbon index derived represents an approximation of the absolute carbon/charcoal content of a sediment sample and should, therefore, allow direct comparisons of charcoal profiles both within and between sites (Winkler, 1984; Patterson *et al.*, 1987). Chemical digestion methods have not, however, been widely adopted (Table 2.1). Robinson (1984), Jones *et al.* (1987) and Bolton (1988) all attempted to apply chemical-assay techniques but encountered problems which led to them being abandoned in favour of pollen slide methods. The principal problems encountered were that fibrous peaty sediments were inadequately digested by standard chemical digests, and that small-scale changes in carbon content (typically only 1-5% of the sediment sample) could not be resolved by the methods.

Table 2.3: The merits and weaknesses of commonly used 'non-pollen slide' charcoal analysis methods.

| Method | Positive points | Negative points |
|---|---|---|
| **Chemical digestion-assay** | 1. 'Absolute % carbon' measure comparable between sediment sequences and sites<br>2. Relatively quick method which doesn't require microscope work | 1. Low sedimentary carbon contents (typically 1-5%) produce unexceptional profiles<br>2. No account for particle size<br>3. No differentiation between carbon from biomass & fossil fuel combustion<br>4. Inefficient in fibrous peats |
| **Petrographic thin section - size class** | 1. Minimal particle fragmentation & loss during preparation<br>2. Contiguous 10 cm samples<br>3. 'Local vs regional' source determination using size classes<br>4. No removal of large particles by sieving<br>5. Appreciation of depositional context of charcoal particles | 1. Extremely time consuming preparation procedure<br>2. Unable to count pollen simultaneously<br>3. Measurement of particles time consuming |
| **Petrographic thin section - point count** | 1. Minimal particle fragmentation & loss during preparation<br>2. Contiguous 10 cm samples<br>3. No sieve removal of large particles by sieving<br>4. Appreciation of depositional context of charcoal particles | 1. Extremely time consuming preparation procedure<br>2. Pollen cannot be counted simultaneously<br>3. No account for particle size |
| **Petri dish method** | 1. Minimal particle fragmentation & loss during preparation<br>2. Minimal uncertainty of identification<br>3. No removal of large particles<br>4. SCPs can be counted simultaneously | 1. Relatively time consuming counting procedure<br>2. Cannot count pollen simultaneously |
| **Sediment slurry - point count** | 1. Minimal particle fragmentation & loss during preparation<br>2. Counting very quick & easy | 1. Unable to count pollen simultaneously<br>2. Uncertainty of identification<br>3. No account for particle size |

A further problem with the technique is that chemical digestion-assay are incapable of discriminating between carbon produced by the combustion of local biomass and that produced by the high temperature combustion of fossil fuels. Sediments deposited during the past century are enriched with industrially derived carbon which can obscure the charcoal record of local catchment fire (Winkler, 1985; Patterson *et al.*, 1987).

Petrographic thin section methods were introduced to lake sediment charcoal studies by Clark (1988). Previously utilised widely in the fields of soil science and geology, Clark (1988; 1989; 1990; Clark *et al.*, 1989) adapted the technique to provide high resolution fire histories of annually laminated lake sediments. The method is particularly effective for the reconstruction of local fire histories because the majority of charcoal particles represented are relatively large (50-10,000 μm in length) and unlikely to have been transported great distances from their point of origin before deposition (Clark, 1988). The large size of the particles also means that they are easily identified, and both size class and point count methods can be used to quantify the charcoal depending upon the objectives of the analysts (Clark, 1982; Clark, 1988; 1989; 1990). Despite the obvious potential of the method it has not been adopted by other analysts, this is probably due to the potentially complex and time-consuming nature of the sample preparation procedure, and the fact that pollen and charcoal cannot be counted simultaneously.

The 'petri dish method' adopted by Simmons and Innes (1981) provides a very simple means of preparing and quantifying charcoal abundance, akin to standard macrofossil analyses. The authors disaggregated peat samples mixed with water in gridded petri dishes and estimated the percentage charcoal cover in each of the grid squares under a binocular microscope at x60 magnification. The advantages of such a simple approach are the speed at which samples can be analysed and the minimal chance of charcoal fragmentation during sample preparation. The disadvantages are equally obvious, despite an estimated error of replicability of only +/- 3% on charcoal estimation (Simmons & Innes, 1981) the accuracy and consistency of such subjective quantification methods are open to doubt. There is, however, no reason why more quantitative counting methods cannot be used with petri dish preparation methods (See Section 3.6).

The sediment slurry preparation procedure developed by Clark (1986) is a further method which is both easy to perform and minimises charcoal particle fragmentation during sample preparation. Aliquots of unadulterated, standardised sediment slurries are mounted on pollen slides under sealed cover slips. Clark (1986) advocated a point count method with this preparation procedure there is no reason why size classes could not be used. It is surprising that no other studies have been based around this technique, despite its obvious merits, most analysts still preferring pollen slide techniques.

## 2.8 The interpretation of charcoal records

Charcoal records represent the most direct evidence of fire in sediments (Wright, 1981). However, the inference of spatial and temporal patterns of fire activity from fluctuations in microscopic charcoal abundance in sediment sequences is an extremely complex process. Many of the problems faced are similar to those encountered in interpreting pollen records (Faegri & Iversen, 1975), but many more are unique to charcoal analyses (Clark, 1983). The aim of the following section is to review and discuss how charcoal data has been interpreted in the past and to provide a synthesis of effective techniques and realistic assumptions for future interpretation. It should be borne in mind from the outset, however, that current inadequacies in the knowledge of charcoal production, dispersal, deposition, sedimentation, sampling and methods of quantification severely restrict the potential reliability and accuracy of fire histories reconstructed using microscopic charcoal analyses (Battson & Cawker, 1983; Anderson & Davis, 1986).

### 2.8.1 The nature of sedimentary charcoal data

Charcoal is produced by the partial or incomplete combustion of plant material, a relatively simple process (Section 2.2). However, before charcoal particles are integrated in a sediment sequence they are subjected to dispersive and depositional processes of unreconstructable form, duration and spatial scale. The charcoal particles are then subjected to further, possibly detrimental, procedures during sample capture, preparation and quantification, before the charcoal profile is produced. Sedimentary charcoal records are, therefore, the products of very complex chains of processes, and are as much, if not more so, the product of the processes which combined to form the sediment assemblage and the methods used to quantify and express the charcoal abundance, as they are the product of the size, intensity, and locality of the parent fires. It is no wonder, therefore, that they are so potentially difficult to interpret.

Palynologists are able to identify the pollen of individual plant taxa and use their relative abundance to reconstruct detailed vegetation histories (Moore *et al.*, 1991). In contrast, with the exception of charred fragments of monocotyledon epidermis, it is not possible to identify the plant taxa or species from which microscopic charcoal particles originate (Clark, 1983; Burney, 1987). The various cellular structures which enable palaeoethnobotanists to identify macroscopic charcoal specimens are not present in the microscopic particles encountered by palaeoecologists (Smart & Hoffman, 1988). Microscopic charcoal analysts, therefore, can only quantify the relative total abundance of charcoal in a sample. This greatly restricts the amount of information to be gained from a microscopic charcoal record, and is analogous to attempting to reconstruct vegetation histories using the total pollen sum alone.

### 2.8.2 Expression of charcoal abundance

The simplest method of charcoal quantification, both practically and theoretically, is to count the number of particles in each sample irrespective of size (e.g. Iversen, 1941; 1969). Charcoal abundance can be expressed as a concentration of particles in a unit volume/weight of sediment (*e.g.* Davis, 1967; Tsudaka & Deevey, 1967; Bradbury *et al.*, 1975; Head, 1980), or preferably given a high degree of dating control as an influx of particles per unit surface area of sediment per year (*e.g.* Amundson & Wright, 1979; Huttunen, 1980; Kodela & Dodson, 1988). Gross changes in particle abundance are interpreted as representative of changing fire activity, abundant charcoal being the product of intensive regional and local fire activity and nominal amounts of charcoal the product of limited fire activity (Patterson et al., 1987).

The quantification of charcoal particles in size classes was introduced to 'maximise' the amount of information attainable from charcoal records (*e.g.* Waddington, 1969; Bradbury & Waddington, 1973; Swain, 1973). A theory based upon the premise that smaller particles are more susceptible to dispersal than larger ones, and that tallying particles by size provides additional information about the proximity of the source fire/fires (Patterson *et al.*, 1987; Clark, 1988). An abundance of large charcoal fragments in a charcoal assemblage is taken to denote local fire activity, whilst a predominance of small particles is indicative of regional rather than local fire activity (*e.g.* Tolonen, 1985; Patterson *et al.*, 1987; Wein *et al.*, 1987; Clark, 1988; Sarmaja-Korjonen, 1992). Indices of total charcoal area in a given sample can also be calculated by summing the areas of the individual particles, providing a measure of charcoal abundance which is a function of both particle frequency and size (*e.g.* Byrne *et al.*, 1977; Cwynar, 1978; Davis, 1979; Green, 1981; Robinson, 1983; Clark, 1986; Burney *et al.*, 1994).

The validity of expressing charcoal abundance in terms of particle size classes and total area indices was questioned by Battson & Cawker (1983). Their argument centred around the fact that as so little is actually confirmed about the differential taphonomy of charcoal particulates of varying size it is inappropriate to interpret charcoal assemblages on such a basis. In addition, charcoal area indices place an artificially inflated importance on larger particles in relation to smaller ones, when it is perhaps more wise to assume that each particle, regardless of size, represents a piece of information of equal importance (Battson & Cawker, 1983). This argument is supported by several studies which have noted that frequencies of large particles are generally simply common when particles of all sizes are common (*e.g.* Mehringer *et al.*, 1977; Patterson *et al.*, 1987; Tipping *et al.*, 1993), the high degree of correlation between size classes found rendering the use of size classes ineffectual for interpretation.

Many studies which perform charcoal analyses in unison with pollen analyses express charcoal abundance as a percentage of the total pollen sum (*e.g.* Hope & Peterson, 1976; Terasmae & Weeks, 1979; Battson &-Cawker, 1983; Edwards, 1985). The assumption is made that pollen and charcoal have approximately similar source areas and are dispersed by similar processes, however, this might not necessarily be the case as further work on charcoal taphonomy is needed. Swain (1973) expressed charcoal abundance as a ratio of total pollen abundance (C:P ratio) in an attempt to distinguish 'true' contemporaneous catchment fires from 'false' peaks in the charcoal record produced by in-washes of charcoal-rich soil or redeposition of sediments in a lake basin. Immediately after a fire in a catchment charcoal abundance should be high and pollen production depressed due to the destruction of the vegetation (Swain, 1973). Many others have adopted the C:P ratio as a means of expressing charcoal abundance, *e.g.* Amundson & Wright, 1979; Head, 1983; Gajewski *et al.*, 1985; Tolonen, 1985; MacDonald *et al.*, 1989; Bennett *et al.*, 1990), but again caution is needed in accepting the assumption that pollen and charcoal are dispersed and deposited by the same processes.

There is no single 'right' way of expressing charcoal abundance, each of those discussed above has both positive and negative points, and a case could be put forward to support the adoption of each. However, given the complex nature of charcoal taphonomy one might be best advised to err on the side of caution and avoid attempts to infer fire proximity on the basis of charcoal particle size, except perhaps with respect to highly localised fire histories reconstructed from soils and peats (See Chapters 4 & 5), and merely express charcoal abundance as a total sum of all particles regardless of their size or area.

### 2.8.3 Source of ignition

'The presence of charcoal in pollen preparations merely tells us that combustible materials have been ignited' (Edwards, 1987) but not how they were ignited. Fires can be started by both natural and anthropogenic means, and it is not possible to determine the ignition source from the microscopic charcoal itself (Clark, 1983). Great care needs to be taken inferring likely causes of ignition. Charcoals formed and deposited before human occupation, or in locations unoccupied by humans, must have been started by natural processes, *i.e.* lightning strikes, volcanic action, sparks from rock falls, or spontaneous combustion (Komarek, 1964; 1968; 1971; 1972), however, during periods of human occupation of an area it is impossible to determine unequivocally whether natural or anthropogenic sources are responsible for igniting fires.

Charcoal records are regularly used, often in conjunction with pollen analyses from archaeological contexts, to infer human modification of the landscape using fire (*e.g.* Simmons & Innes, 1981; Chambers *et al.*, 1988; Mitchell, 1990; Charman, 1992). The coincidence of abundant charcoal with declining arboreal pollen in Neolithic or later sediments is often attributed to anthropogenic woodland clearance (Edwards, 1985; Bennett *et al.*, 1990). However, although the circumstantial evidence for such an explanation is strong, especially since major natural fires in Britain are rare (Rackham, 1980; Day, 1993), it is by no means a certainty. Evidence of considerable numbers of contemporary fires being ignited by natural processes, particularly lightning strikes, should be used a healthy level of caution, *e.g.* Cwynar (1977) estimates that 48.5% of modern fires in Canadian wildwood were started by lightning.

### 2.8.4 What information can be gained from microscopic charcoal assemblages?

A fundamental consideration when interpreting sedimentary charcoal records is whether individual fires can be resolved? Swain (1973) and Byrne *et al.* (1977) were able to identify individual fire events in lake sediment records, however, they used extremely high resolution sampling strategies and annually laminated sediments. The vast majority of charcoal analyses conducted, however, use low intensity sampling regimes, and the diffuse nature of the boundaries between adjacent stratigraphic units (caused by sediment mixing and redeposition), dictate that individual fires can not be detected (Terasmae & Weeks, 1979; Edwards, 1990). Whilst it is tempting to interpret all of the pronounced peaks in charcoal records as representative of individual fires (Tolonen, 1978, 1983), most charcoal records are no more than histories of the relative importance of fire in the general environment around sediment sinks and should be interpreted as such (Patterson *et al.*, 1987; Edwards, 1990). Too many charcoal records are perhaps over-interpreted.

What can be inferred from charcoal records about fire frequency, size, intensity, and location in the landscape? Extremely highly resolved fire records can be reconstructed using high resolution analyses of contiguously sampled laminated sediments (Clark, 1988; Clark *et al.*, 1989; Peglar, 1993), and in some instances it may be possible to determine the frequency of individual fires. The unequivocal reconstruction of the size, intensity, and position of individual fires in the landscape, however, is impossible using single lake or terrestrial sediment cores (Tolonen, 1983; 1986; Patterson *et al.*, 1987; Clark *et al.*, 1989).

Each and every charcoal profile should be interpreted individually and in isolation within their own unique context, generalisations should be avoided wherever possible. Listed below, however, are some cautious guidelines useful for interpreting relatively low resolution fire records: low charcoal contents generally represent periods when few or no large fires occurred locally (Huttunen & Tolonen, 1977; Tolonen, 1978); high charcoal levels suggest fire frequency was possibly higher, although, it is not necessarily possible to determine whether the fires burned locally or regionally (Winkler, 1985); the height of charcoal peaks is not a good indication of fire proximity because local fires do not necessarily produce more prominent peaks than regional fires (Swain, 1973); and, in order to confirm the local origin of the charcoal source one is best advised to use indirect measures such as charcoal:pollen ratios, varve thickness (Swain, 1973), mineral magnetic measurements (Rummery *et al.*, 1981), aluminium and vanadium influxes (Cwynar, 1977), or abrupt changes in ash and mineral contents of the sediment (Tolonen, 1980) in addition to charcoal records.

It is impossible to distinguish changes in fire frequency from changes in fire intensity in the sediment charcoal records of the majority of catchments (Singh *et al.*, 1981). Relatively high and low frequencies and/or intensities of fire are both generally expressed by respectively high and low relative proportions of charcoal in the sediment. More charcoal, however, may be deposited in sediments after a high intensity fire than a low intensity fire or a series of low intensity fires because: firstly, more charcoal is produced as more combustible material is burnt; secondly, a high intensity fire is likely to burn a greater area of the catchment; and thirdly, removal of more of the vegetation cover may allow greater runoff and more charcoal to be washed into the sedimentary sink (Singh *et al.*, 1981). Patterson & Sassaman (1988) also suggest that 'other things being equal, intense fires or repeated low-intensity fires, should result in greater accumulations of sedimentary charcoal than infrequent, low-intensity ones'.

More charcoal does not, however, necessarily mean more fires (Clark, 1983). Not only do the quantities of charcoal produced by individual fires vary greatly but dispersal and deposition processes can have an overriding influence on the form of sedimentary charcoal records. As a result, rather than using the abundance of charcoal to provide an indication of fire frequency Clark (1983) suggests that the form of the curve is more important. In general, more frequent fires produce a smoother curve than less frequent ones, and less frequent fires tend to show greater difference between charcoal content maxima and minima (Clark, 1983; Sarmaja-Korjonen, 1991).

*In situ* fires in peat or soil profiles may be identifiable by the presence of conspicuous microscopic charcoal layers, macroscopic charcoal remains, or evidence of obvious *in situ* charring of surface organic matter and litter (Tolonen, 1985, 1987).

### 2.8.5 Interpretation of charcoal assemblages from lakes in which sediment mixing or focusing may have occurred.

Pennington (1979) addressed the problem of determining whether sediment mixing had affected pollen assemblages in lake sediments by expressing pollen abundance in several formats, as a concentration, as an influx and as a percentage of the total pollen sum, and by contrasting the signals provided by each. Contemporaneous changes in all three measures are most likely to reflect real changes in pollen influx to the lake, and changes occurring due to focusing tend to show up as changes in pollen influx without a correlative change in concentration (Pennington, 1979). A similar methodology could be adopted with respect to microscopic charcoal assemblages.

A number of independent indices have also been formulated to aid and corroborate the correct interpretation of charcoal records in lacustrine environments. The Charcoal:Pollen ratio introduced by (Swain, 1973) has been adopted by a number of authors as an effective means of distinguishing charcoal peaks of local and regional origin (*e.g.* Cwynar, 1978; Swain, 1978; Huttunen, 1980; Patterson & Sassaman, 1988; Sarmaja-Korjonen, 1992). However, differential focusing of pollen and charcoal suggests that the final deposition of the more buoyant microscopic charcoal particles will only occur in the calmest areas of a lake in contrast to pollen which will be sedimented over a generally larger area, leading to an over representation of charcoal relative to pollen in the focal points of lakes (Odgaard, 1993). This must have implications for the validity of Charcoal:Pollen ratios. Edwards & MacDonald (1991) provided an excellent example to highlight such problems. Six cores taken from different locations in Loch Doon revealed marked variations in the charcoal profiles implying disparities in the depositional processes between cores. Interestingly, however, the profiles for alder pollen exhibited much less variation between cores, suggesting less significant redeposition within the pollen population, and marked differential focusing between the charcoal particles and the alder pollen.

Other indirect confirmatory evidence of 'local' fire activity has also been gained by equating charcoal peaks with abrupt and contemporaneous changes in the following parameters: varve thickness (Swain, 1973; Cwynar 1977); influx of vanadium and aluminium (Cwynar, 1977); abrupt increases in sedimentary ash and mineral contents (Tolonen, 1978); declines in *Picea* pollen (Tolonen, 1978); sudden but temporary changes in diatom assemblages (Tolonen, 1980); an enormous rise in magnetic minerals (Rummery *et al.*, 1979; 1981). The most reliable interpretations will be gained by using as many of these indices together as possible.

# Chapter 3: Methods

**Abstract**

The locations, descriptions and selection criteria of the sites used in this study are outlined. The methods used to produce maps of post-1940/50 muirburn on Tulach Hill, Perthshire, from aerial photographs are presented along with the coring and palaeoenvironmental laboratory techniques adopted to produced extended fire histories from microscopic charcoal analyses. The microscopic charcoal analysis methods developed for this study are described and discussed.

## 3.1 Site selection

### 3.1.1 Sites for the studies of soil core muirburn history reconstruction and charcoal taphonomy around muirburns

Six heather-dominated moorland sites in Perthshire, Scotland were chosen for a study to determine whether microscopic charcoal analyses of moorland soil profiles could be used to reconstruct extended fire histories. The ultimate aim of the study being to ascertain whether dates of last burning for heather stands could be effectively estimated by this method. The locations of the sites, Tulach Hill, Trochry Hill, Auldallan Hill, Blacklaw Hill, Happas Farm and Gallow Hill, are shown on Figure 3.1. Table 3.1 provides a summary of relevant site characteristics.

These sites were selected because they fulfilled a number of criteria. All of the sites are readily accessible, all have relatively thick mor humus soils (>20 cm) and all have a range of different aged heather-stands (the result of management burning over extended periods), including some particularly old stands which aerial photograph analyses suggest have not been burned during the post-1940/50 period (Kirkpatrick, 1992).

Figure 3.1: The locations of the sites used in the studies of muirburn history reconstruction and charcoal taphonomy around muirburns.

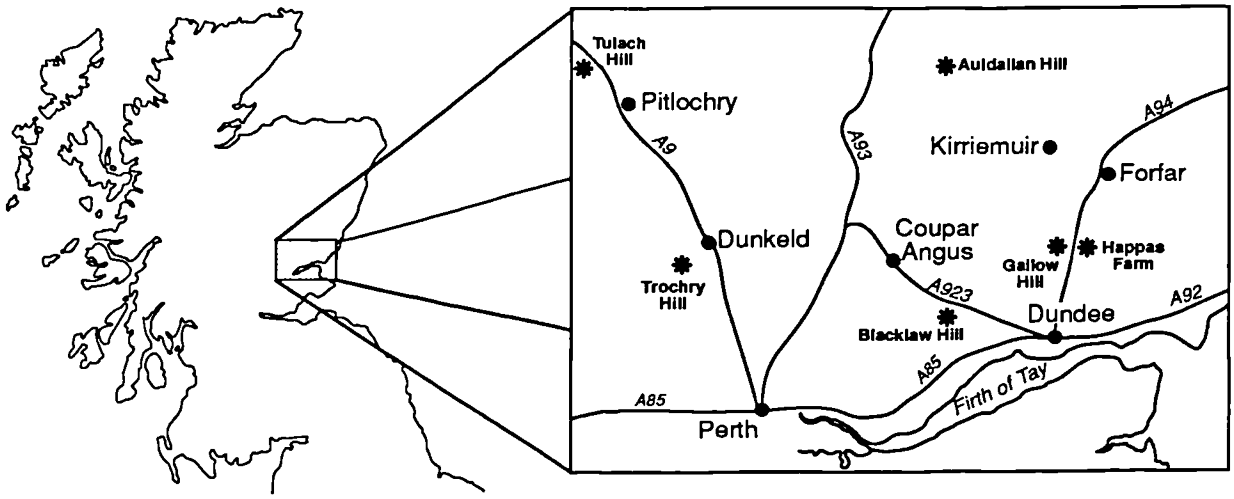



Table 3.1: Summary of site characteristics.

| | Tulach Hill | Trochry Hill | Auldallan Hill | Blacklaw Hill | Happas Farm | Gallow Hill |
|---|---|---|---|---|---|---|
| **Grid reference** | NN8663 | NN987385 | NO315590 | NO290335 | NO445409 | NO395410 |
| **Altitude** | 300-460 m | 310 m | 360 m | 200 m | 170 m | 340 m |
| **Geology** | Schists and limestone | Schists and greywakes | Altered millstone grits | Igneous basalt & dolerite | Lower Old Red Sandstone | Lower Old Red Sandstone |
| **NVC* classification** | H12/H16 | H10/H16 | H16 | H10 | H21 | H10 |
| **Soil type** | Peaty Podsol | Peaty Podsol | Iron-rich Podsol | Iron-rich Podsol | Peaty Podsol | Iron-rich Podsol |

* National Vegetation Classification (Rodwell, 1991).

Tulach Hill was selected as the principal site for the development of the soil profile charcoal analysis techniques because of the exceptional aerial photographic coverage of the site, a time-series of eight aerial photographs, taken in 1950, 1959, 1965, 1969, 1976, 1980, 1985 and 1988 respectively was available of the site. The comprehensive temporal and spatial record of muirburn activity on the moor, reconstructed from the aerial photographs, was used to identify the approximate dates when individual locations on the moor were last burned. The effectiveness of the charcoal analysis technique was ascertained by analysing soil cores from locations for which the date of last burning were known.

The Tulach Hill site was also used for a study of charcoal taphonomy from muirburns, again utilising the excellent aerial photograph cover and charcoal analysis of soil cores.

### 3.1.2 Sites for studies of peat erosion and *Calluna* loss

Seven lacustrine sites were chosen for the study of long-term peat erosion and *Calluna* loss (Figure 3.2). The sites were selected from the extensive network of UK and Irish sites sampled for the Surface Waters Acidification Project (SWAP) (Battarbee *et al.*, 1988; Patrick *et al.*, 1989) which were made available by the Department of Geography, University College London. The seven selected sites fulfilled a number of important criteria: firstly, each had experienced both marked losses of *Callunetum* (Stevenson & Thompson, 1993) and episodes of peat erosion (Stevenson, 1992) in their catchments during the last millennium; secondly, all are headwater lakes with accordingly small pollen source areas (Peck, 1973; Bonny, 1976) and negligible networks of inflowing streams to minimise inputs of streamborne pollen and charcoal (Jacobson & Bradshaw, 1981; Birks *et al.*, 1990); the cores from them all had been dated by-either $^{210}Pb$ methods alone or a combination of $^{210}Pb$ and $^{14}C$ methods; and lastly, detailed loss-on-ignition (LOI) and pollen analyses had been conducted on the cores (Stevenson, 1992; Stevenson & Thompson, 1993).

Figure 3.2: Locations of sites for the studies of peat erosion and *Calluna* loss.

**Lough Muck, Donegal, Republic of Ireland (B 194 408)**

| | |
|---|---|
| *Altitude:* | 210 m. |
| *Lake size & depth:* | Area 36 ha; depth 19 m maximum; 2 very short minor tributaries. |
| *Catchment size:* | 25 ha (excluding lake). |
| *Geology:* | Predominantly granite. |
| *Soils:* | Considerable areas of fairly flat blanket peats which is in some places undergoing, or has undergone, active erosion. |
| *Vegetation:* | Acid moorland dominated by *Molinia* grassland with *Calluna vulgaris* occurring on the drier ground. |

**Blue Lough, County Down, Northern Ireland (J 328 252)**

| | |
|---|---|
| *Altitude:* | 340 m. |
| *Lake size & depth:* | Area 2.1 ha; depth 5 m maximum; circular shape; no discrete inflow. |
| *Catchment size:* | 35 ha (excluding lake); rises steeply to the north (703 m elevation) in a steep headwall. |
| *Geology:* | Entirely granite. |
| *Soils:* | Thin blanket peat in the less steep areas & bare granite rock and scree on the northern slope. |
| *Vegetation:* | *Calluna vulgaris* dominated, ranging from young vigorous plants in burned areas to mature and leggy stands. |

**Loch Teanga, South Uist, Outer Hebrides, N.W. Scotland (NF 818 383)**

| | |
|---|---|
| *Altitude:* | 25 m. |
| *Lake size & depth:* | Area 7 ha; depth 21 m maximum; steeply shelving rock margins; no significant drainage streams. |
| *Catchment size:* | 33 ha (excluding lake). |
| *Geology:* | Lewisian Gneiss |
| *Soils:* | Abundant blanket peat. |
| *Vegetation:* | *Calluna* dominated heath, extensively burned for sheep. |

**Llyn Conwy, Gwynedd, Wales (SH 780 463)**

| | |
|---|---|
| *Altitude:* | 450 m. |
| *Lake size & depth:* | Area 40 ha; depth 22 m maximum. |
| *Catchment size:* | 189 ha (excluding lake). |
| *Geology:* | Ordovician Rhyolite. |
| *Soils:* | Blanket peat. |
| *Vegetation:* | *Calluna* dominated. |

**Round Loch of Glenhead, Galloway, S.W. Scotland (NX 450 804)**

| | |
|---|---|
| *Altitude:* | 300 m. |
| *Lake size & depth:* | Area 12.5 ha; depth 13.5 m maximum |
| *Catchment size:* | 95.1 ha (excluding lake). |
| *Geology:* | Tonalite (Loch Doon granite). |
| *Soils:* | Deep peats and peaty podsols; skeletal soils and bare rock on the steeper slopes. |
| *Vegetation:* | Dominated by *Molinia caerulea* with *Erica cinerea* & *Trichophorum cespitosum*; also common *Calluna vulgaris*, *Nardus stricta*, *Potentilla erecta* & *Narthecium ossifragum*. |

**Loch Na Larach, N.W. Scotland (NC 217 583)**

| | |
|---|---|
| *Altitude:* | 61 m. |
| *Lake size & depth:* | Area 9.5 ha; depth 8.5 m maximum. |
| *Catchment size:* | 54 ha (excluding lake). |
| *Geology:* | Moine Gneiss. |
| *Soils:* | Blanket peat. |
| *Vegetation:* | *Molinia* & *Calluna* dominated. |

**Loch Tanna, Arran, N.W. Scotland (NR 921 428)**

| | |
|---|---|
| *Altitude:* | 315 m. |
| *Lake size & depth:* | Area 32.9 ha; depth 3 m maximum; very shallow for its size. |
| *Catchment size:* | 300.4 ha (excluding lake). |
| *Geology:* | Granite. |
| *Soils:* | Dominated by blanket peats. |
| *Vegetation:* | Mature *Calluna*, with *Molinia* and *Eriophorum* on the wetter ground. |

### 3.2 Aerial photograph analyses

PC ARC/INFO (Environmental Systems Research Institute, 1989), a desk-top geographical information system (GIS), was used to digitise muirburns from a time-series of eight aerial photographs of the Tulach Hill study area (1950, 1959, 1965, 1969, 1976, 1980, 1985 and 1988). The monochrome aerial photographs ranged in scale from approximately 1:8,000 to 1:20,000, stereo-pairs were not used. Errors in image translation, due to camera tilt, are believed to be minimal since near perfect matches were found when the digitised images of burns visible on more than one photograph were overlaid. The accuracy of interpretation was checked by locating burns from the 1988 aerial photograph in the field.

Aerial photograph analyses at Auldallan Hill, Blacklaw Hill, Gallow Hill, Trochry Hill and Happas Farm were performed by Dr H. Kirkpatrick (Kirkpatrick, 1992). Individual burn coverages were traced onto acetate sheets, combined, and annotated onto a recent AP to be used to locate burns in the field (Kirkpatrick, 1992; Stevenson *et al.*, 1996).

### 3.3 Coring techniques

#### 3.3.1 Mor humus soil cores

The mor humus soil cores (<10 cm in length), sixteen at Tulach Hill and one each at Trochry Hill, Auldallan Hill, Blacklaw Hill, Happas Farm and Gallow Hill, were taken by inserting sharpened 8 cm diameter plastic drainpipes into the soil. The cores were wrapped in plastic to prevent desiccation and transported to the laboratory where they were sectioned using a hand wound ram and sharp blade. Apart from the unconsolidated surface litter the cores were sectioned into contiguous 2 mm slices.

### 3.3.2 Lake sediment cores

The seven lake cores were taken between 1984 and 1988 by members of the PRU/ECRU at UCL. Loch Teanga, Round Loch of Glenhead and Llyn Conwy were cored from a stable anchored platform using a square-rod Livingstone corer and a piston corer to sample the uppermost sediment (Jones *et al.*, 1989). Short cores, approximately 80 cm long, were recovered from Blue Lough, Lough Muck, Loch Tanna and Loch Na Larach using a mini-Mackereth corer (Mackereth, 1969).

## 3.4 Laboratory analyses

### 3.4.1 Pollen analysis

Samples for pollen analysis were prepared and counted using standard methodologies (Moore *et al.*, 1991) by Professor A.C. Stevenson, Department of Geography, University of Newcastle upon Tyne between 1986 and 1991.

### 3.4.2 Percentage loss-on-ignition (LOI)

Known weights of homogenised dry sediment were placed in weighed crucibles and ignited in a muffle furnace at $550^0$C for two hours. The crucibles of sediment were allowed to cool in a desiccator before reweighing. The loss of sediment mass was taken to represent the organic carbon content of the sample. The LOI analyses were performed by members of the PRU/ECRU in the Department of Geography, UCL.

### 3.4.3 Sediment geochemistry

Concentrations of the trace metals (Pb, Zn, Ni, Cd) were determined for the seven lake cores by flame atomic absorption spectrophotometry, after digestion of the sediment by hydrofluoric, nitric and perchloric acids (Rippey, 1990). The trace metal analyses were conducted by Dr B Rippey, University of Ulster, Freshwater Laboratory, Traad Point, Ballyronan, Northern Ireland.

### 3.4.4 Dating techniques

#### 3.4.4.1 Radiometric techniques

The upper sediments of the seven lake cores were dated using gamma spectrometry analysis of $^{210}Pb$, $^{226}Ra$, $^{137}Cs$ and $^{241}Am$ (Appleby *et al.*, 1986) in the Department of Applied Mathematics and Theoretical Physics at the University of Liverpool (see Appendix 5). The $^{210}Pb$ chronologies for the Round Loch of Glenhead and Loch Teanga cores were augmented with $^{14}C$ dates carried out by the Scottish Universities Research & Reactor Centre at East Kilbride (Jones *et al.*, 1989) (see Appendix 6).

### 3.4.4 Spherical carbonaceous particle analysis

Funds were not available for radiometric dating of the mor humus soil profiles. SCPs were, therefore, used to provide isochrones for relative dating (Renberg & Wik, 1984; 1985a; Wik & Natkanski, 1990; Rose, 1991; Rose *et al.*, 1995). Spherical carbonaceous particles (SCPs) were quantified for all of the mor humus soil cores. The SCPs (> *c.* 10 μm in diameter) were counted at the same time as the charcoal, in the petri dish charcoal preparations, under a stereo-microscope at x40 magnification, a method similar to that used by Renberg & Wik (1984; 1985a; 1985b). See Section 3.5 for the sediment sample preparation procedure.

## 3.5 A method for the preparation of lake sediment and soil samples for microscopic charcoal analysis

(1) Place 0.2g of air dry sediment in a 250 ml conical flask. Add 20 ml of distilled water, cover and leave for 24 hrs to allow the sediment to rehydrate.

0.2g of sediment proved sufficient for both the mor humus soil and lake sediment samples. Larger sediment samples reduce counting efficiency because the sediment slurries produced spread too thickly over the petri dish and obscure charcoal particles.

(2) Add 20 ml of 6% hydrogen peroxide, cover and leave in an oven at $50^0$C for 48 hrs.

This stage is designed to initiate the bleaching of the dark organic component of the sediment samples. No attempt is made to totally remove this organic component, the aim of the preparation is merely to bleach the dark organic material so that the black charcoal particles are readily recognisable under the microscope. A series of digests with a wide range of different $H_2O_2$ strengths was conducted to determine the minimum concentration of the reagent which would facilitate sufficient bleaching. 6% $H_2O_2$ produces adequate bleaching of the organic component and does not fragment or cause the loss of microscopic charcoal particles (White & Hannus, 1981).

(3) Filter through a Whatman No.1 filter paper (pore size ~11 microns). Retain the contents of the filterpaper and dispose of the supernatant.

Filtering is necessary to remove the dark organic leachate produced by the last stage. If the filtering process is performed carefully nominal quantities of charcoal particles and SCPs are lost. Filtering was preferred to centrifugation as a means of separating the organic material from the superfluous liquid because it is much less likely to cause charcoal particle fragmentation (Clark, 1984).

(4) Wash the filtrate into a 9 cm diameter plastic petri-dish using distilled water. In an oven at $50^0$C evaporate away the excess water, until the samples are barely covered in liquid.

Evaporating the excess water ensures that any discrepancies in the amounts of water used to wash the organic samples into the petri dishes are redressed before more reagents are added. Care should be taken to ensure that the samples are not fully dehydrated because this may cause charcoal particle fragmentation.

(5) Add 20 ml of 6% hydrogen peroxide, cover and leave in an oven at $50^0$C for 48 hrs.

A second mild digest to bleach any remaining dark organic material. Plant fragments with diameters of up to several millimetres require this extra bleaching.

(8) In an oven at $50^0$C evaporate off the excess liquid until the samples are dry. The samples are now ready to count.

*N.B.* All samples for each core should be prepared in a single batch, ensuring that all of the samples from a core receive exactly the same preparation procedure. Differences in charcoal particle abundance and size class distribution between samples from individual cores are, therefore, very unlikely to be the result of differential particle fragmentation caused by preparation procedures.

### 3.6 Charcoal quantification

Two separate charcoal counting strategies were used, one for the mor humus soil cores and a second for the lake cores. Both sets of samples were, however, prepared by the laboratory method described above.

#### 3.6.1 Mor humus soil cores

Charcoal counts were conducted at a magnification of x40 under an Olympus VH20 stereoscopic microscope with top lighting provided by a Schott fibre optic light source. The charcoal particles were tallied into six size classes of 16-31 μm, 31-63 μm, 63-125 μm, 125-250 μm, 250-500 μm and >500 μm in length using an eyepiece graticule. Particles >500 μm in length were measured individually. Particles smaller than 16 μm were ignored because correct identification could not be assured.

### 3.6.2 Lake sediment cores

Charcoal in the lake sediment samples was quantified under a magnification of x160 using the same stereoscopic microscope equipment described above. The greater magnification was necessary because the charcoal particles were considerably smaller than those encountered in the soil cores. Only the absolute numbers of particles per sample were counted, the charcoal particles were not quantified in size classes. Size classes were not used because it was felt that such small particle sizes provide little, if any, additional information above that attained from absolute abundance counts (see Section 2.3.4).

### 3.6.3 Recovery rate

An experiment was conducted to determine whether the preparation procedure removed or fragmented microscopic charcoal particles. Charred twigs collected from a moorland fire were ground with a pestle and mortar to produce microscopic charcoal particles. Six sub-samples of the charcoal were counted in size classes, subjected to the preparation procedure outlined in Section 3.5, and then recounted. The results are shown in Table 3.2.

Table 3.2: The effect of the charcoal preparation procedure on six charcoal assemblages.

| | Charcoal samples (B=before & A=after the preparation procedure) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
| Size class | B | A | B | A | B | A | B | A | B | A | B | A |
| <16 μm | 47 | 39 | 37 | 38 | 49 | 49 | 19 | 15 | 62 | 65 | 71 | 55 |
| 16-31 μm | 82 | 92 | 90 | 90 | 82 | 79 | 66 | 48 | 93 | 93 | 93 | 88 |
| 31-63 μm | 86 | 84 | 62 | 69 | 79 | 77 | 56 | 63 | 81 | 87 | 78 | 72 |
| 63-125 μm | 18 | 12 | 25 | 18 | 24 | 26 | 31 | 29 | 33 | 31 | 20 | 27 |
| 125-250 μm | 7 | 5 | 6 | 8 | 13 | 20 | 14 | 18 | 11 | 14 | 11 | 15 |
| 250-500 μm | 9 | 10 | 8 | 8 | 6 | 11 | 6 | 11 | 15 | 15 | 13 | 15 |
| >500 μm | 3 | 3 | 1 | 1 | 1 | 2 | 1 | 1 | 4 | 6 | 5 | 6 |
| Total | 252 | 245 | 229 | 232 | 254 | 263 | 192 | 183 | 299 | 311 | 291 | 278 |

The total numbers of particles and the size class distributions of the six charcoal assemblages before and after preparation are very similar, indicating that the preparation procedure causes very little particle fragmentation or loss. The minor differences between the total numbers of particles in the pre- and post-preparation counts, between 1.3% for Sample 2 and 4.7% for Sample 4, are probably due to observer error and the nature of the counting process. Charcoal particles are not regular in shape and dimension, and variations in particle orientation between counts may well lead to slight discrepancies in counts. Overall, however, the results of the experiment are very encouraging illustrating that the sample preparation procedure does not cause excessive amounts of charcoal particle fragmentation or loss, and that the counting procedure has a good level of replicability.

### 3.6.4 Discussion

The charcoal sample preparation procedure outlined above was developed to fulfil a number of criteria specific to this project. The principal aim was to minimise particle fragmentation during preparation because the particles were to be quantified in size classes. This was achieved by keeping the chemical and physical stresses placed on the charcoal particles to a minimum by using dilute organic oxidants and avoiding rigorous mechanical processes such as mixing and centrifuging. The method developed is simple, quick, cheap and effective with both mor humus and lake sediments.

The second consideration was that SCPs could be counted simultaneously with the charcoal, saving both preparation and counting time. No other charcoal method yet developed allows the analyst to do this. Although, the method of SCP quantification adopted may be less accurate than the methods developed by Rose (1990) or Renberg & Wik (1984), the results are satisfactory for the purpose of this study (See Section 4.4.2).

A further advantage is that charcoal particle identification is much more effective and reliable using uncovered petri dishes under a stereomicroscope than on pollen slides under a transmitted light microscope. The identification of particles can be verified by changing their orientation or observing how they fracture when pressed with a sharp instrument. Charcoal particles fracture tangentially in a fashion which makes them readily distinguishable from pyrite and other black minerals (Bolton, 1988).

The charcoal particles in the mor humus cores were quantified in six size classes in an attempt to ascertain whether information about fire proximity could be obtained from the size class distributions (See Section 3.1). Many authors have tallied charcoal particles in size classes (*e.g.* Waddington, 1969; Swain, 1973, 1978; Clark, 1988) but there has been no standardisation of either the number used or the dimensions of the size classes adopted (Appendix 2). Six size classes were used in this study, the minimum number deemed necessary to gain an effective insight into changes in charcoal assemblage structure, greater numbers of size classes make counting laborious and time consuming. The dimensions of the size classes are based on the squares of a gridded eyepiece graticule, with squares of 63 μm on a side. The wide range of particle sizes, between 16 μm and >500 μm, ensure that significant differences in dispersal distances and patterns might be expected (Clark, 1988a). Geometrically progressive size classes were adopted because the number of fragments in a given size class has been shown to decrease exponentially as size class increases (Patterson *et al.*, 1987). The low magnification (x40) used on the samples from the mor humus cores ensured that only relatively large charcoal particles were counted. Particles of these proportions are believed most likely to provide a record of local or *in situ* fire activity (Clark, 1988a). Particles smaller than 0.25 of a grid square were not quantified because correct identification could not be guaranteed.

The charcoal particles recovered from the lake sediment cores were markedly smaller than those in the mor humus cores, over 80-90% were <20 μm in length. As a consequence they were counted under x160 magnification to try to ensure correct identification. The lacustrine charcoal particles were not tallied into size classes because their small size, the restricted range of particle sizes, and the possibility of mixing and focusing in the lake basin after initial deposition (Davis, 1973; Davis & Brubaker, 1973; Odgaard, 1992), negate their usefulness for determining source areas (See Section 2.4.3).

### 3.7 Statistical analyses.

Microsoft EXCEL 5 was used for all exploratory data analysis (Microsoft Corporation, 1994). CANOCO (ter Braak, 1990) was used for the multivariate statistical analyses. Details of the various techniques used are presented in the relevant sections.

# Chapter 4: Analyses of mor humus soil cores

**Abstract**

Aerial photograph and microscopic charcoal analyses of mor humus moorland soil cores are used to develop a technique for reconstructing long-term fire histories for specific locations on moorland. Sub-fossil charcoal assemblages produced by *in situ* fires are shown to be distinguishable from those produced by nearby *ex situ* fires on the basis of charcoal particle abundance and size class distribution. Extended fire histories (>50 years) are produced for specific locations on six different Perthshire moors.

## 4.1 Introduction

Moorland ecology, and particularly the relationship between burning and vegetation dynamics, has been studied intensively (*e.g.* Gimingham, 1972; Mallik & Gimingham, 1983; Hobbs & Gimingham, 1984; Gimingham & Hobbs, 1987; Maltby *et al.*, 1990). The vast majority of these studies have, however, been conducted over very short time-scales, and the long-term community dynamics are relatively poorly understood (May, 1994; Legg, 1995). A number of key questions concerning moorland ecology require longer-term perspectives to elucidate them, *e.g. Calluna* growth cycles, nutrient cycling processes and the reasons why *Callunetum* is declining on a national scale (Stevenson & Thompson, 1993; Thompson *et al.*, 1995; Smidt, 1995). Palaeoecological analyses can provide the long term perspective necessary to address such issues.

Fossil microscopic charcoal analyses have been used in moorland contexts but the majority have concentrated on catchment or regional scales and produce relatively low resolution fire histories (Iversen, 1941, 1969; Odgaard, 1988, 1992; Charman, 1992). The aim of this study is to assess the extent to which microscopic charcoal analyses of moorland soils can be used to provide highly temporally and spatially resolved extended fire histories. Techniques to reconstruct accurate long-term fire histories (>100 years) of individual vegetation stands would allow the impact of prolonged muirburn management on moorland communities and the effects of different burning periodicities to be assessed.

Aerial photographs can be used to reconstruct the burning histories of individual heather stands for the past forty to fifty years (Hester and Sydes, 1992), however, the reconstruction of muirburn histories beyond the limit of aerial photographic analyses is problematical. Even the most conscientiously kept estate records cannot provide stand-specific burning histories on a time-scale of several centuries. Traditionally charcoal and palynological studies have been conducted on lake or peat sediments, few have been conducted on catchment soils (Dimbleby, 1964; Iversen, 1964, 1969). In order to produce fire histories for individual locations in moorland landscapes soil cores need to be used.

A number of potential problems may be important in restricting the efficacy of palaeoecological analyses of soils. The following questions need answering:

- Can individual fires be resolved in mor humus soil matrices? Soils accumulate at relatively slow rates (approximately 0.24 - 0.61 mm $yr^{-1}$ at Tulach Hill; Table 4.7) and resultant palaeo-records are consequently of low temporal resolution. In a moorland, where areas of vegetation may be burned on 10-15 year rotations, the sediment record of fire must be able to resolve individual fires on such time-scales.
- Can charcoal assemblages produced by *in situ* fires be discerned from those produced by *ex situ* ones in the soil charcoal record? Moorland managed by muirburn is characterised by large numbers of small, discrete fires set on an annual basis. Large quantities of microscopic charcoal are likely to be produced and if dispersal and redistribution rates of charcoal are high this could cause considerable problems for interpreting sediment charcoal profiles. 'Background' charcoal, *i.e.* non-local or 'old' re-mobilised charcoal, may mask or complicate records of contemporary local fire activity.
- Do moorland fires destroy the upper soil horizons removing the record of former fire activity? Moorland fires are surface fires whose principle fuels are vegetation and litter on the soil surface, problems in reconstructing extended fire histories may arise if subsequent fires remove surface sediments.

### 4.2 Outline of methodology

The aim of this study was to develop a technique to reconstruct unequivocal, high resolution long-term histories of fire activity from moorland soils, in order that dates of last burning and burn frequency/periodicity could be estimated. In order to achieve this the following methodology was devised.

- Use aerial photographs to reconstruct the recent (post-1940/50) muirburn history of a moor.

- Collect mor humus soil cores from locations on the moor with different post-1940/50 burning histories, *i.e.* some that had been burned once, some twice and some not at all but at known distances from fires.
- Conduct microscopic charcoal analyses on the soil cores. Do the fire histories produced by the charcoal analyses agree with those produced by AP analyses? Are the soil records of sufficient resolution for individual fires to be distinguishable?
- Use discriminant analyses to differentiate charcoal assemblages produced by *in situ* and *ex situ* fires. Can charcoal assemblages produced by *in situ* fires be reliably discriminated from those produced by nearby *ex situ* ones on the basis of their particle size distributions?
- Use the knowledge gained from the recent fire histories to extend the charcoal fire histories to pre-aerial photograph age sediments using charcoal analyses.
- Apply the palaeoecological techniques developed at Tulach Hill to a number of other sites to test the effectiveness of the methods elsewhere.

### 4.2.1 Site selection rationale

Tulach Hill, Blair Atholl, Perthshire was chosen as the main site for developing soil core charcoal analyses. The primary reason that Tulach Hill (Figure 3.1) was chosen as the site for studying patterns of past muirburn was the excellent aerial photograph coverage available, eight APs spanning the period between 1950-1988, allowed a comprehensive assessment of post-*c.*1940/50 fire activity on the moor. The site was also suitable for charcoal analyses because the mor humus soils which cover the majority of the moor are well developed (>20 cm depth) and relatively homogenous providing suitable sediment sequences for palaeoecological investigation.

The sites at Auldallan Hill, Blacklaw Hill, Gallow Hill, Trochry Hill and Happas Farm (Figure 3.1) were used as sites at which to test the charcoal analysis techniques developed at Tulach Hill. These sites were chosen because they are readily accessible, have relatively thick mor humus soils and some particularly old stands of heather not burned during the post 1940/50 period (assessed by aerial photograph analyses; Kirkpatrick, 1992).

### 4.2.2 Aerial photograph analysis of post-1940/50 muirburn on Tulach Hill

The time-series of eight aerial photographs from Tulach Hill, 1950, 1959, 1965, 1969, 1976, 1980, 1985 and 1988, provided a particularly comprehensive coverage from which to

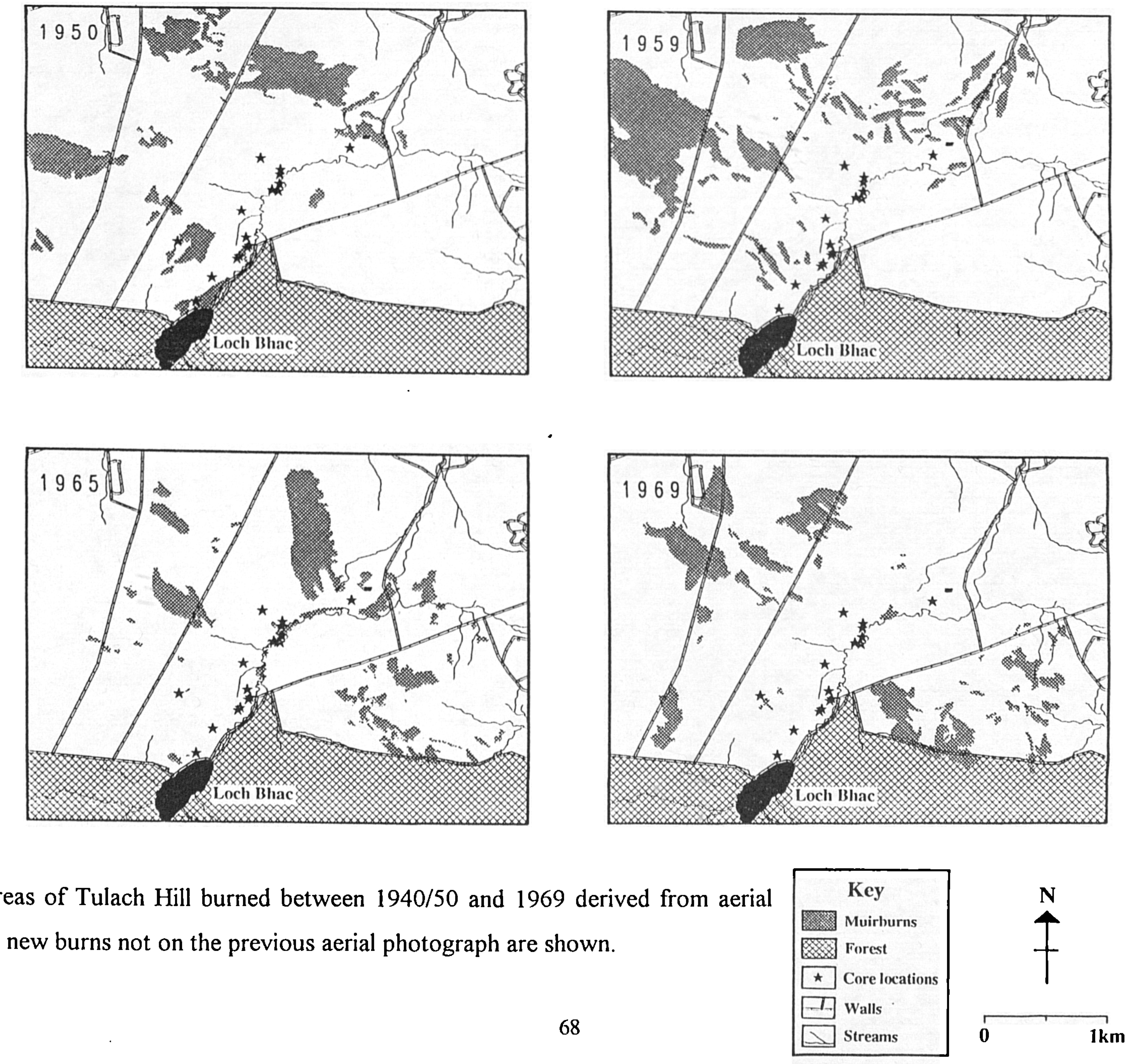
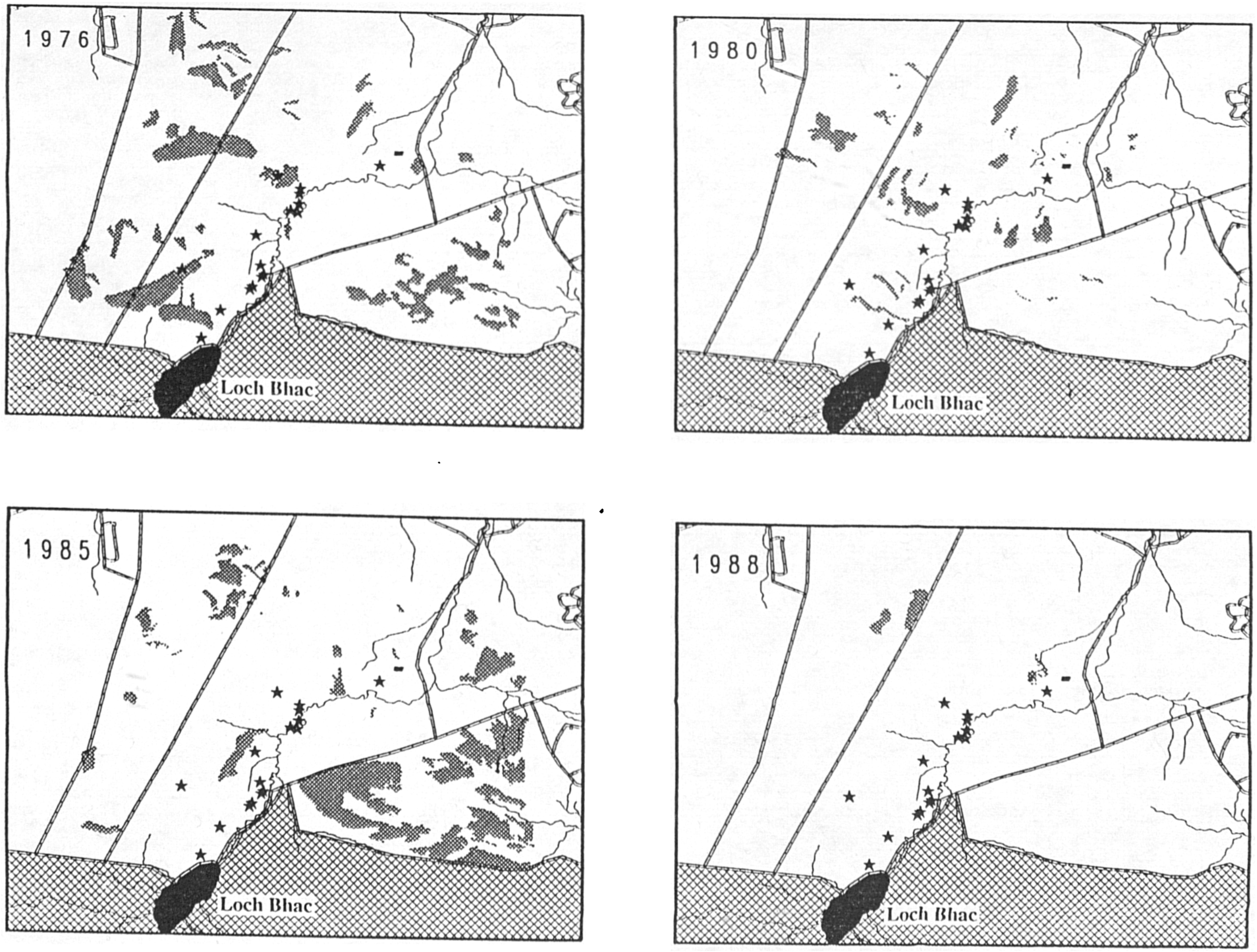



Figure 4.1: The areas of Tulach Hill burned between 1940/50 and 1969 derived from aerial photographs. Only new burns not on the previous aerial photograph are shown.



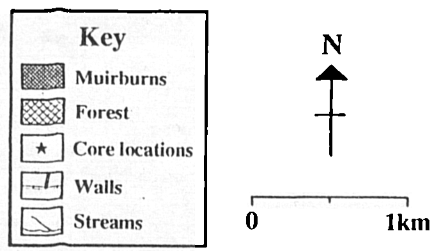




Figure 4.2: The areas of Tulach Hill burned between 1970 and 1988 derived from aerial photographs. Only new burns not on the previous aerial photograph are shown.

reconstruct the recent temporal and spatial patterns of burning of vegetation on the moor. ARC/INFO (ESRI, 1989), a desk-top geographical information system (GIS), was used to capture and manipulate the aerial photograph information. Previous methods, which involved tracing muirburns from photographs on to acetate sheets by hand, were rather primitive and inaccurate (Hester & Sydes, 1992; Kirkpatrick, 1992), the GIS approach is much more effective, increasing the speed and accuracy of data capture and allowing greater manipulation and analysis of the data.

On dry heather-dominated moorland Hester and Sydes (1992) estimate that all patches of muirburn remain visible on APs for at least 7 years, ninety percent of them for at least eight years, and some may remain visible for up to 13/15 years. At Tulach Hill because the intervals between APs were less than 7 years in all but one case, 1950-59, practically all fires can be guaranteed to be presented on the muirburn summary maps (Figures 4.1 & 4.2). The longevity of burned patches on photographs meant that considerable numbers of burns were visible on successive APs, only new burns not visible on a previous aerial photograph are presented on Figures 4.1 and 4.2. Figures 4.1 and 4.2 provide accurate maps summarising the spatial and temporal patterns of muirburn on Tulach Hill over the period from *c.*1940/50 to present.

### 4.2.3 The reconstruction of fire histories from mor humus soils

Sixteen soil cores were collected from the locations depicted by stars on Figures 4.1 and 4.2. Suitable core locations were identified from the maps of past burning produced by the AP analyses. A range of locations with varied post-*c.*1940/50 burning histories were selected, *i.e.* some that had been burned once only, some which had been burned twice and some which had escaped burning during this period. A map of coring locations was drawn on a recent AP, and an EDM was used to locate core locations in the field by triangulation. A number of constraints determined which areas could be cored. Open moorland is relatively homogeneous and it can be very difficult to locate oneself accurately within swathes of open vegetation, even using features from aerial photographs. Core locations in close proximity to readily identifiable landmarks, *i.e.* fences, path junctions *etc,* were therefore chosen. Only very small areas of moorland had been burned frequently, the more times a patch had been burned the smaller it tended to be, and consequently the more difficult it is to locate in the field. No locations on Tulach Hill which had been burned more than twice, were large enough or near enough to obvious ground features for them to be reliably determined. Four cores were taken from locations burned only once, two from areas burned twice, and ten from positions not burned at all during the post-1940/50 period.

In order to provide fire histories of the highest possible resolution, and because of concerns about the slow accumulation rate of the soils (Table 4.7), the cores were sectioned where possible into contiguous 2 mm thick samples. The sample preparation and counting methods outlined in Chapter 3 were used to reconstruct the fire histories, Figures 4.3 - 4.10.

In order to verify that the fire history reconstruction methods developed at Tulach Hill were applicable to other moorlands the analyses were conducted on mor humus soil cores from a further five sites. The sites are all in the Tayside region, Auldallan Hill, Blacklaw Hill, Gallow Gill, Happas Farm and Trochry Hill (Figure 3.1).

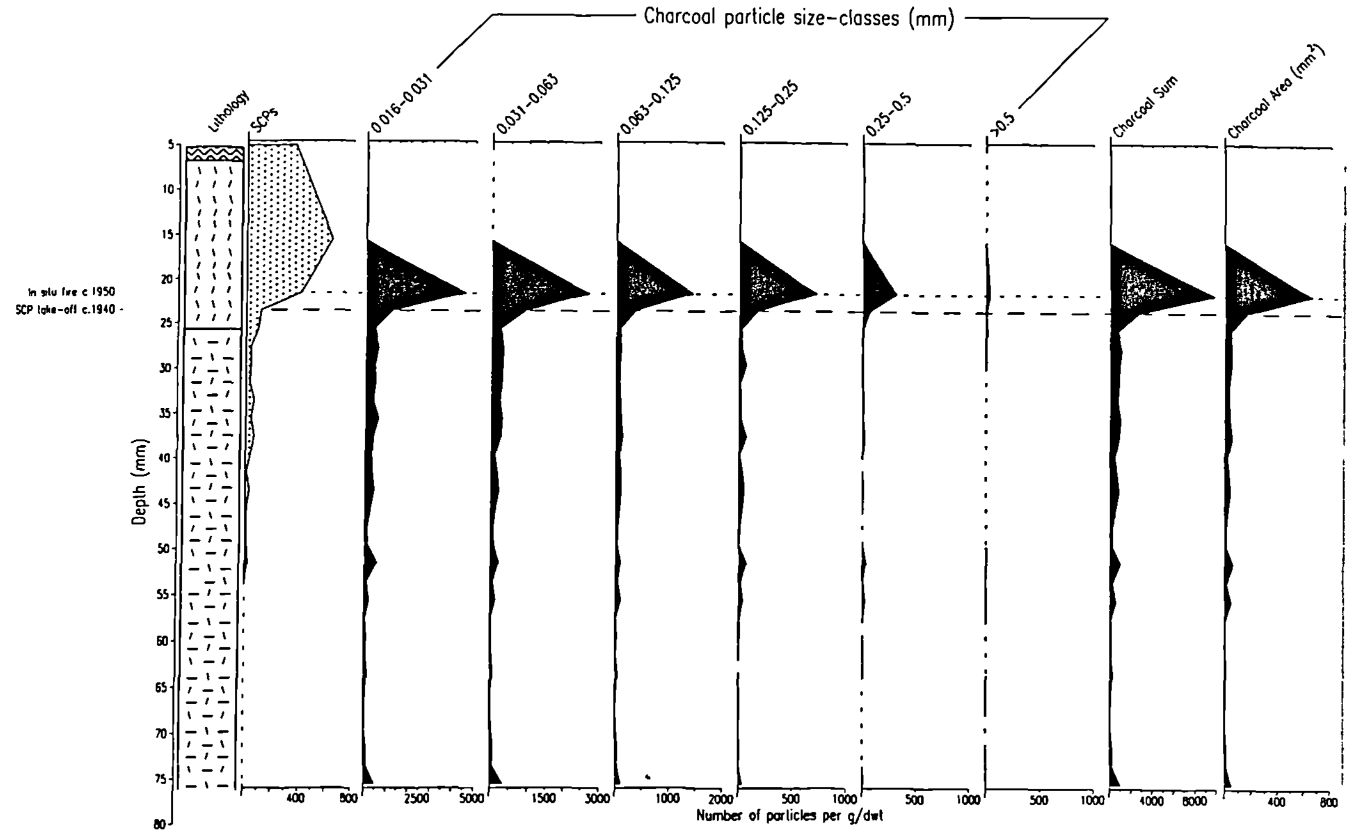
Preliminary aerial photograph analyses performed by Dr H. Kirkpatrick (1992) suggested that the locations cored had not been burned post-*c.*1940. The cores were processed in exactly the same manner as those from Tulach Hill with the additional aim of determining when the locations on the moor had been last burned (part of a project conducted by Professor A.C. Stevenson on nutrient cycling and the effects of heather burning; Stevenson (1994)).

#### 4.2.4 Spherical carbonaceous particle analysis

All SCPs greater than approximately 10 μm in diameter were quantified in all of the sediment samples in which charcoal was counted using the method outlined in Section 3.4.4.2. Rates of SCP recovery using this method are much poorer than those obtained by the methods outlined by Rose (1991) and Renberg & Wik (1984) because of the less rigorous digestion of organic material during sediment sample preparation. Undigested organic material in the samples, including charcoal, may obscure some SCPs during the counting procedure. Notwithstanding this, however, the technique provides a comparatively quick and satisfactorily effective means of deriving approximate SCP profiles (Figures 4.3-4.10 and 4.13-4.15).

Figure 4.3: Charcoal profiles from the Tulach Hill mor humus soil cores *Tulach 1* and *Tulach 2*.

Tulach 1: Charcoal profile.




Tulach 2: Charcoal profile

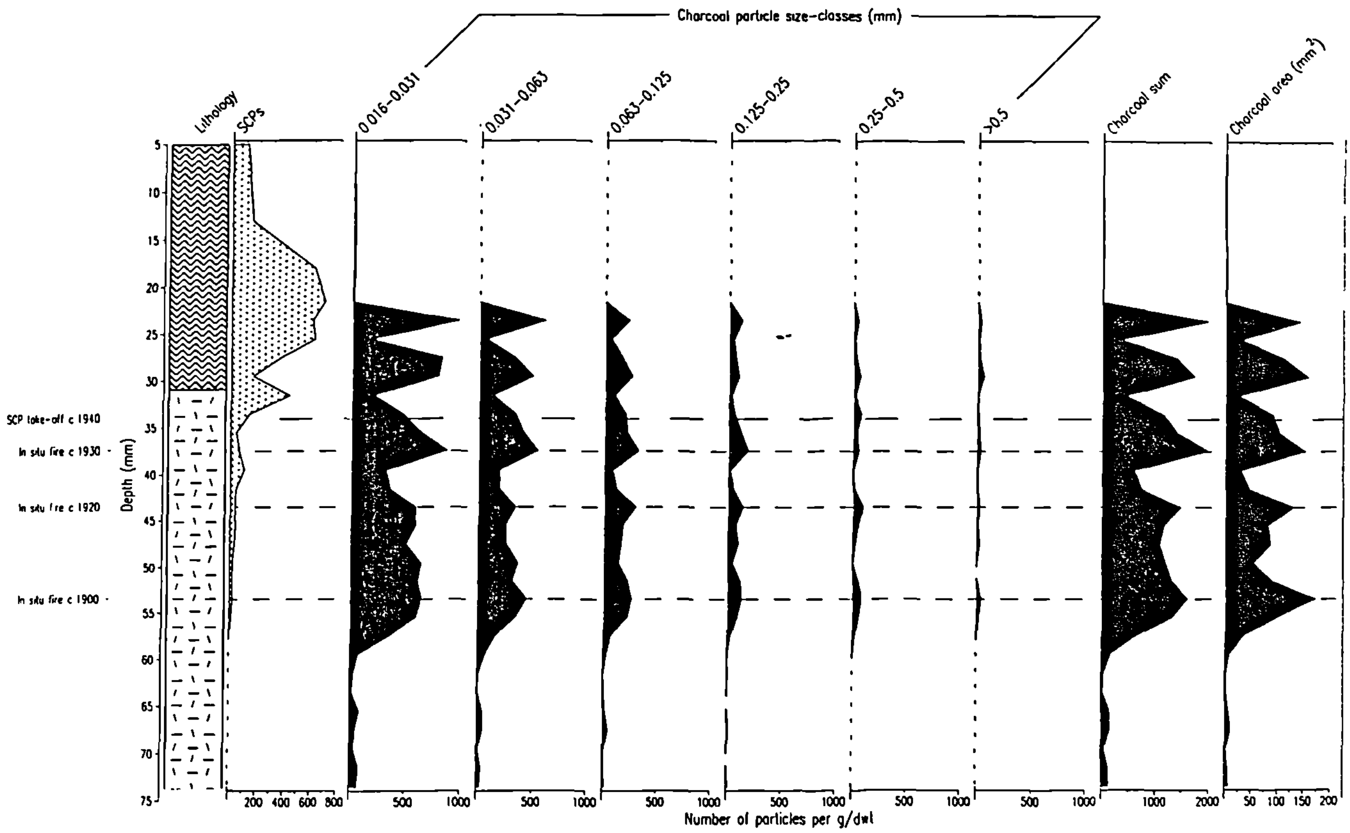
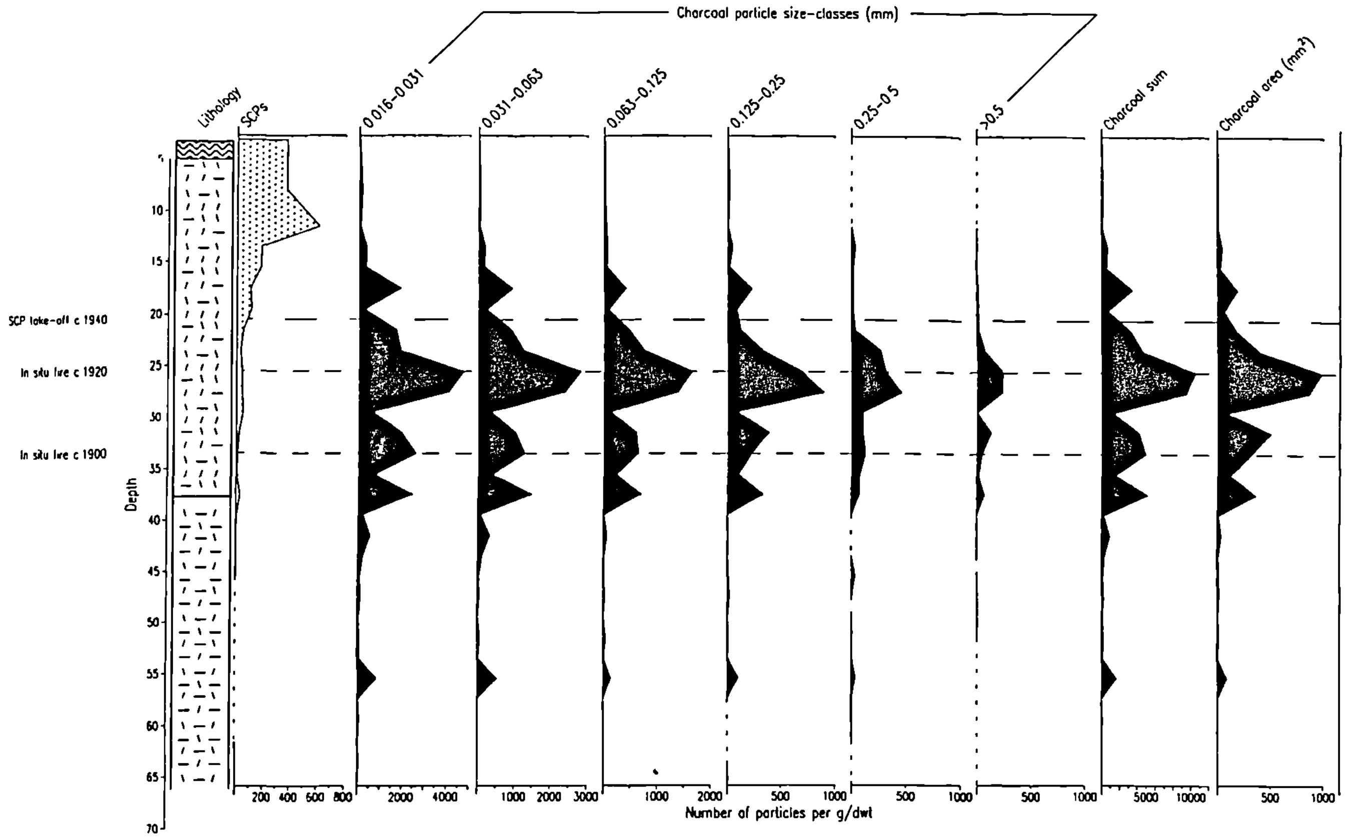


Figure 4.4: Charcoal profiles from the Tulach Hill mor humus soil cores *Tulach 3* and *Tulach 4*.

Tulach 3: Charcoal profile




Tulach 4: Charcoal profile

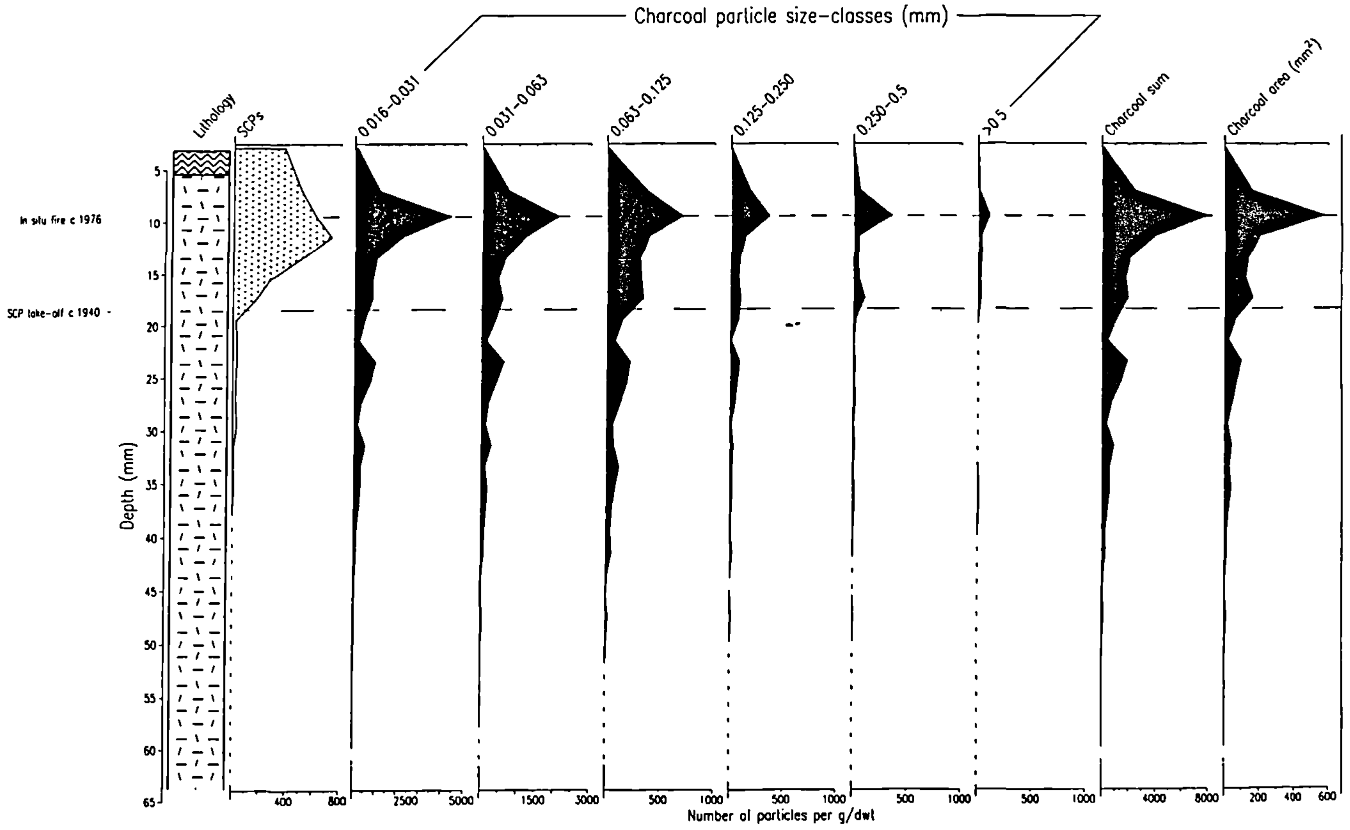
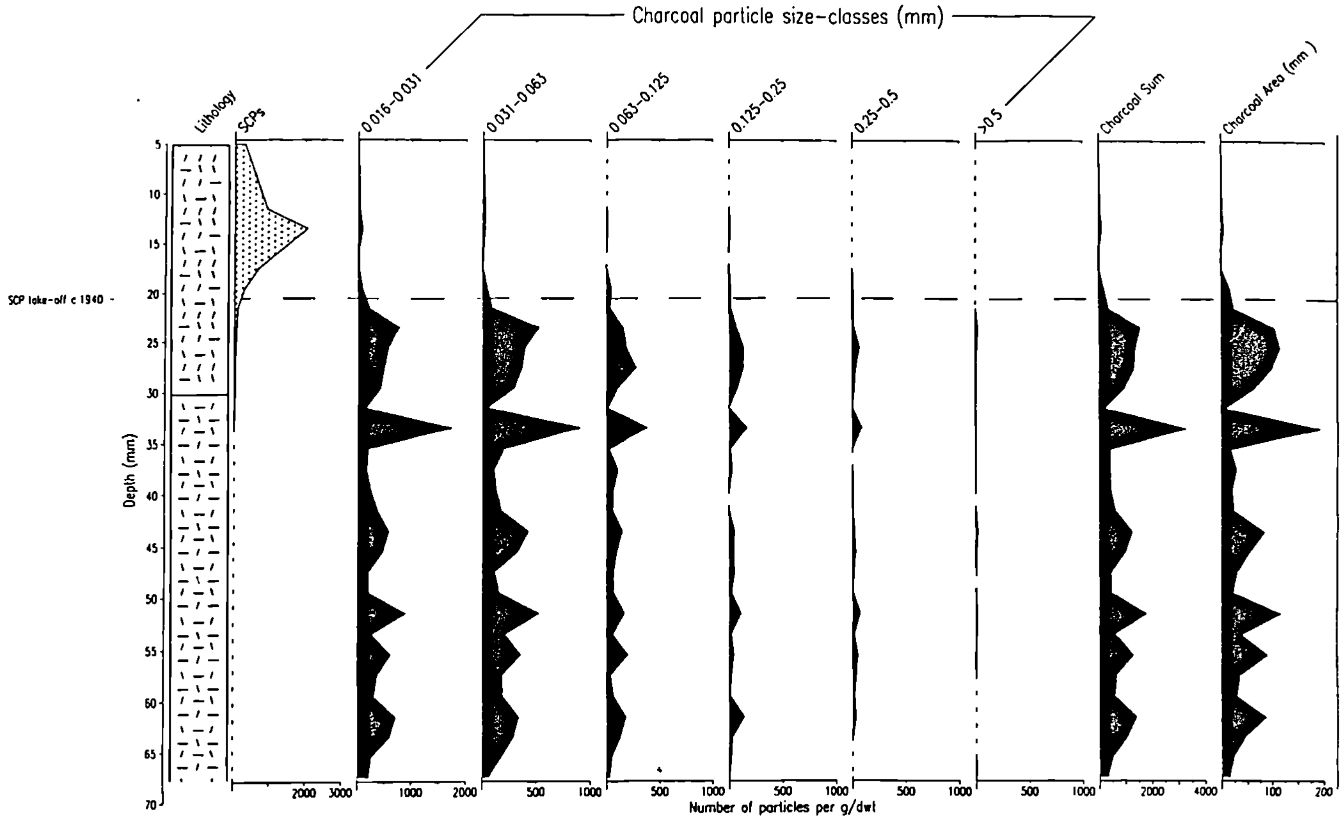


Figure 4.5: Charcoal profiles from the Tulach Hill mor humus soil cores *Tulach 5* and *Tulach 6*.

Tulach 5: Charcoal profile.




Tulach 6: Charcoal profile

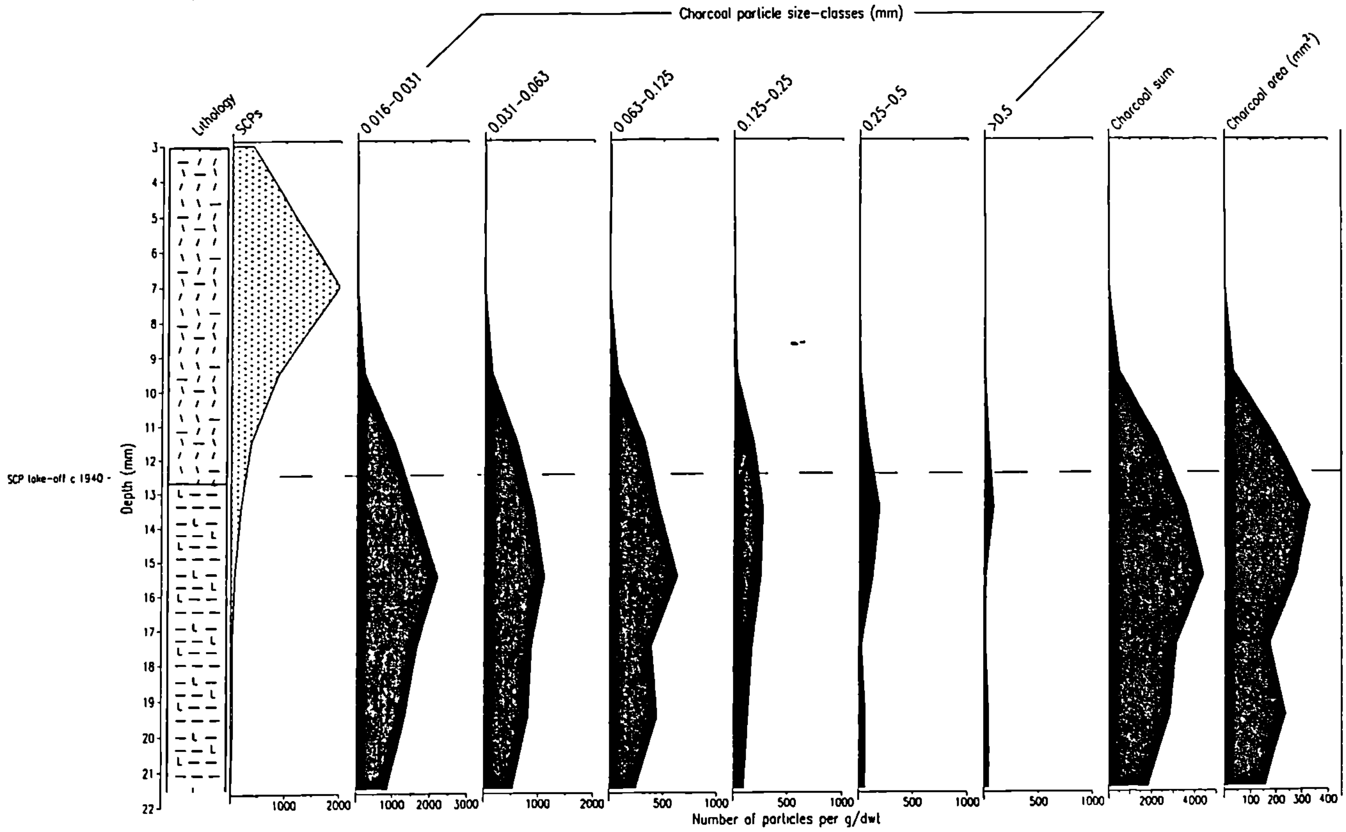
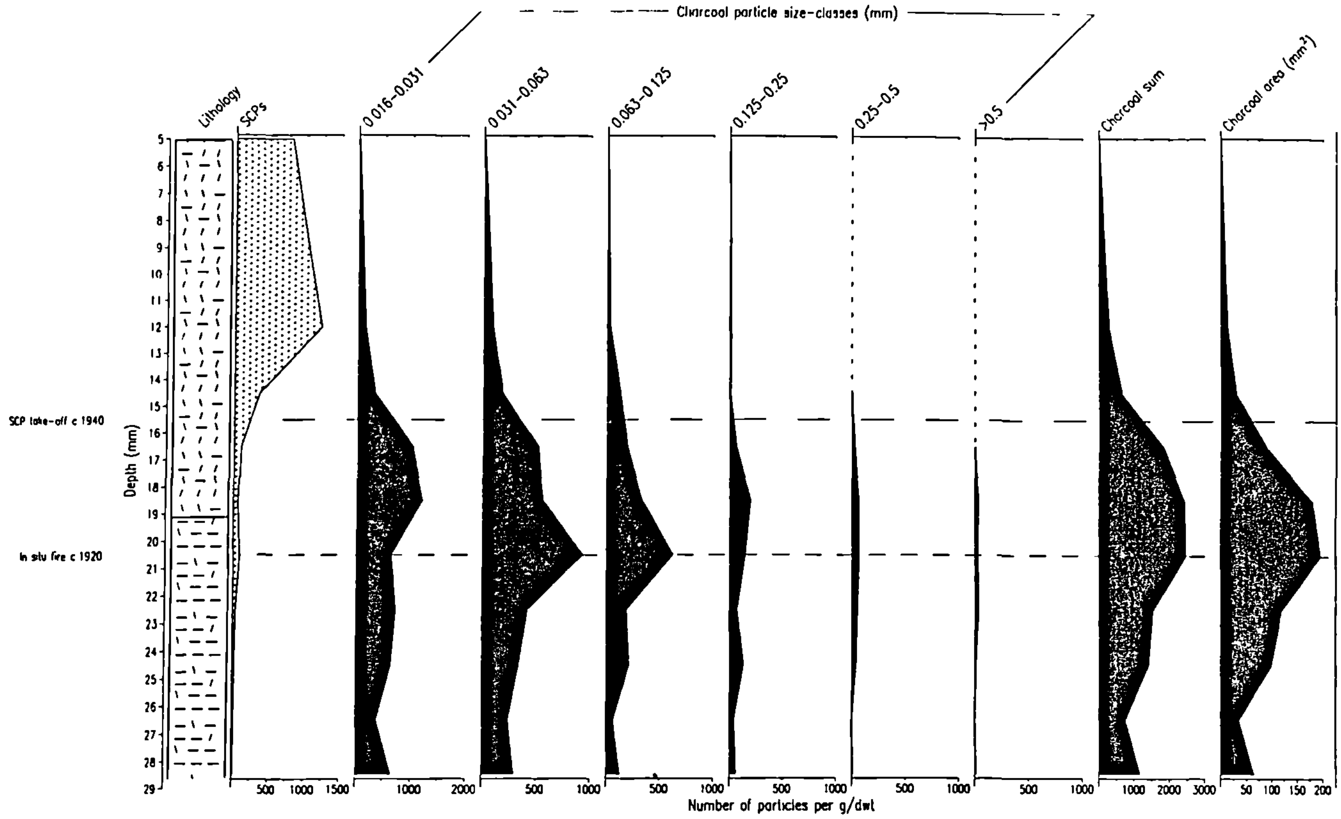


Figure 4.6: Charcoal profiles from the Tulach Hill mor humus soil cores *Tulach 7* and *Tulach 8*.

Tulach 7: Charcoal profile




Tulach 8: Charcoal profile

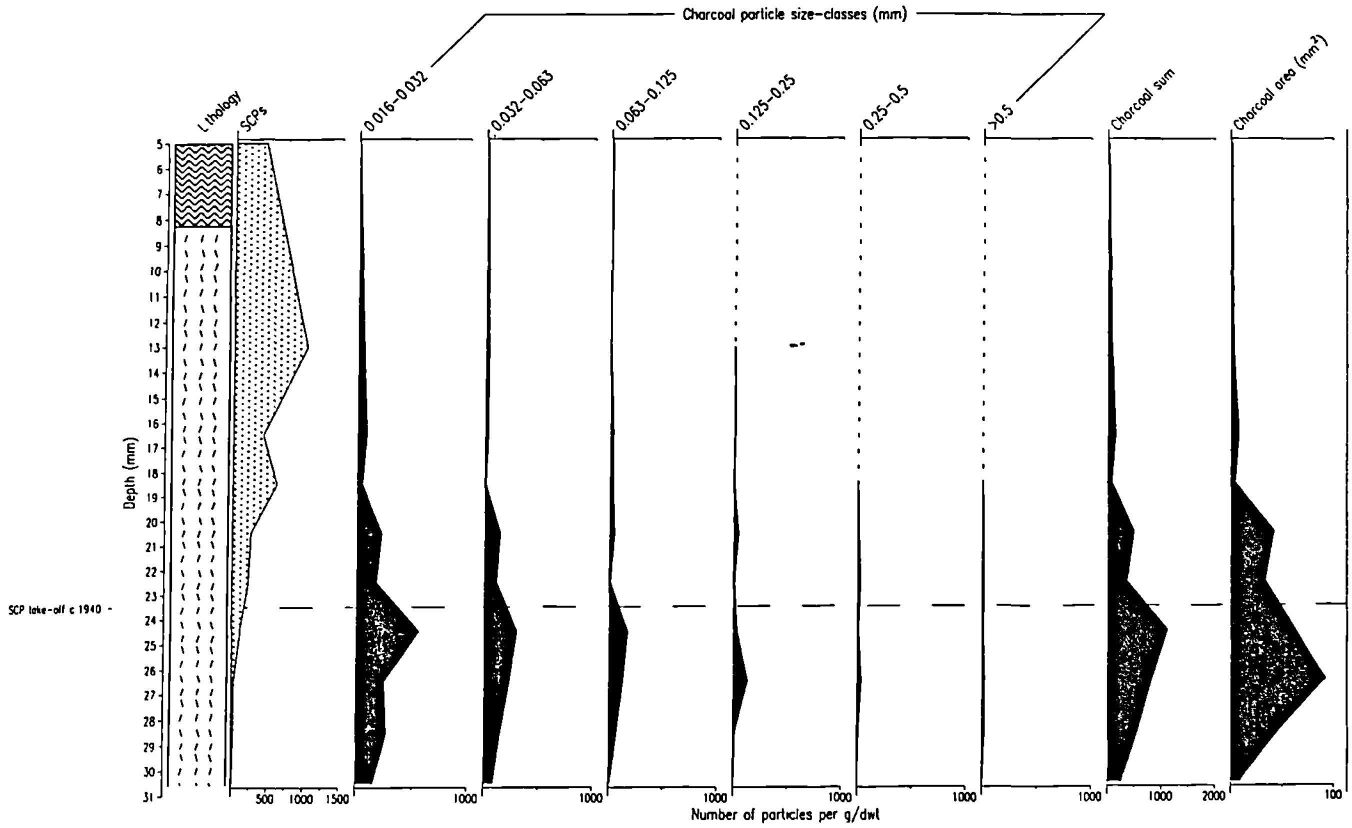
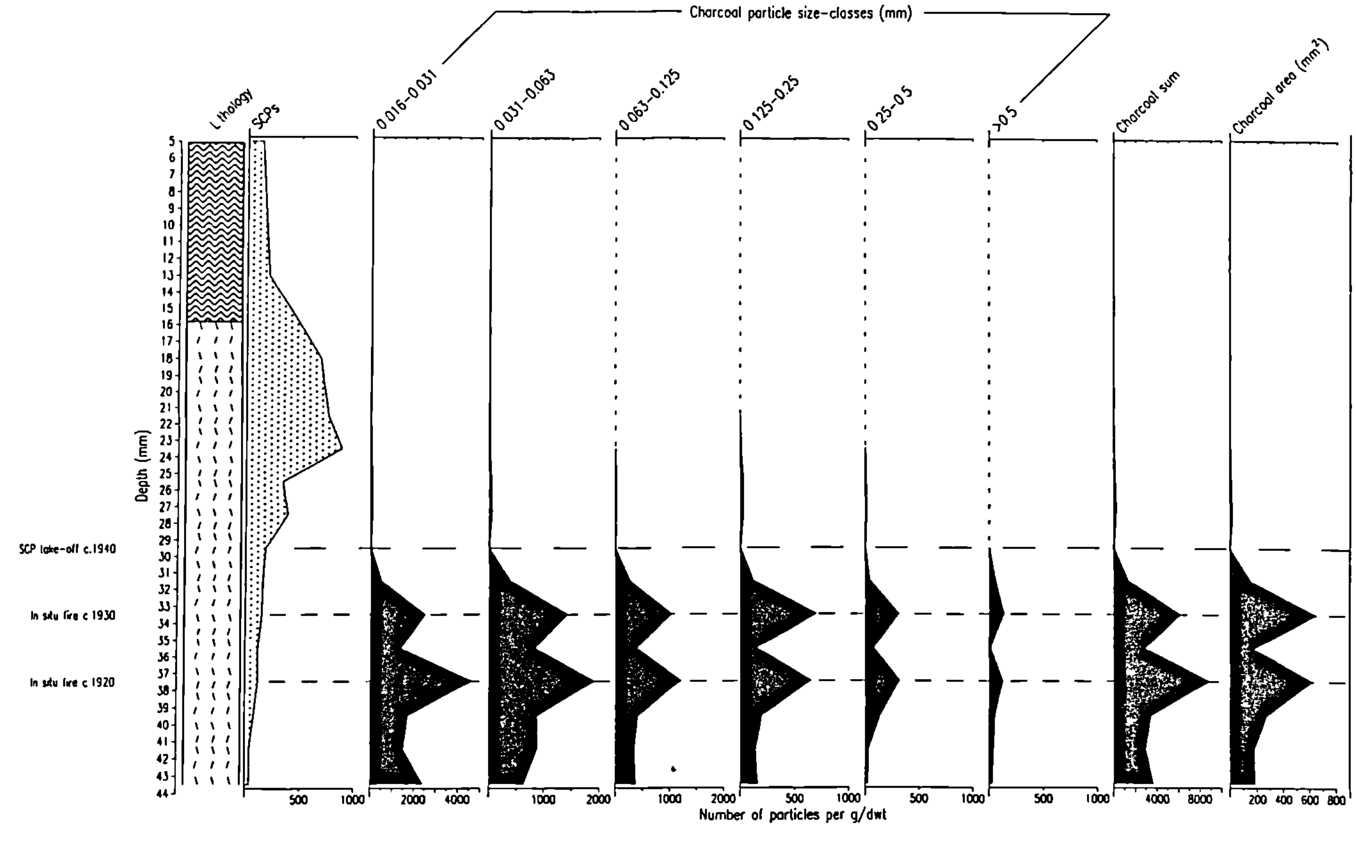


Figure 4.7: Charcoal profiles from the Tulach Hill mor humus soil cores *Tulach 9* and *Tulach 10.*

Tulach 9: Charcoal Profile




Tulach 10: Charcoal profile

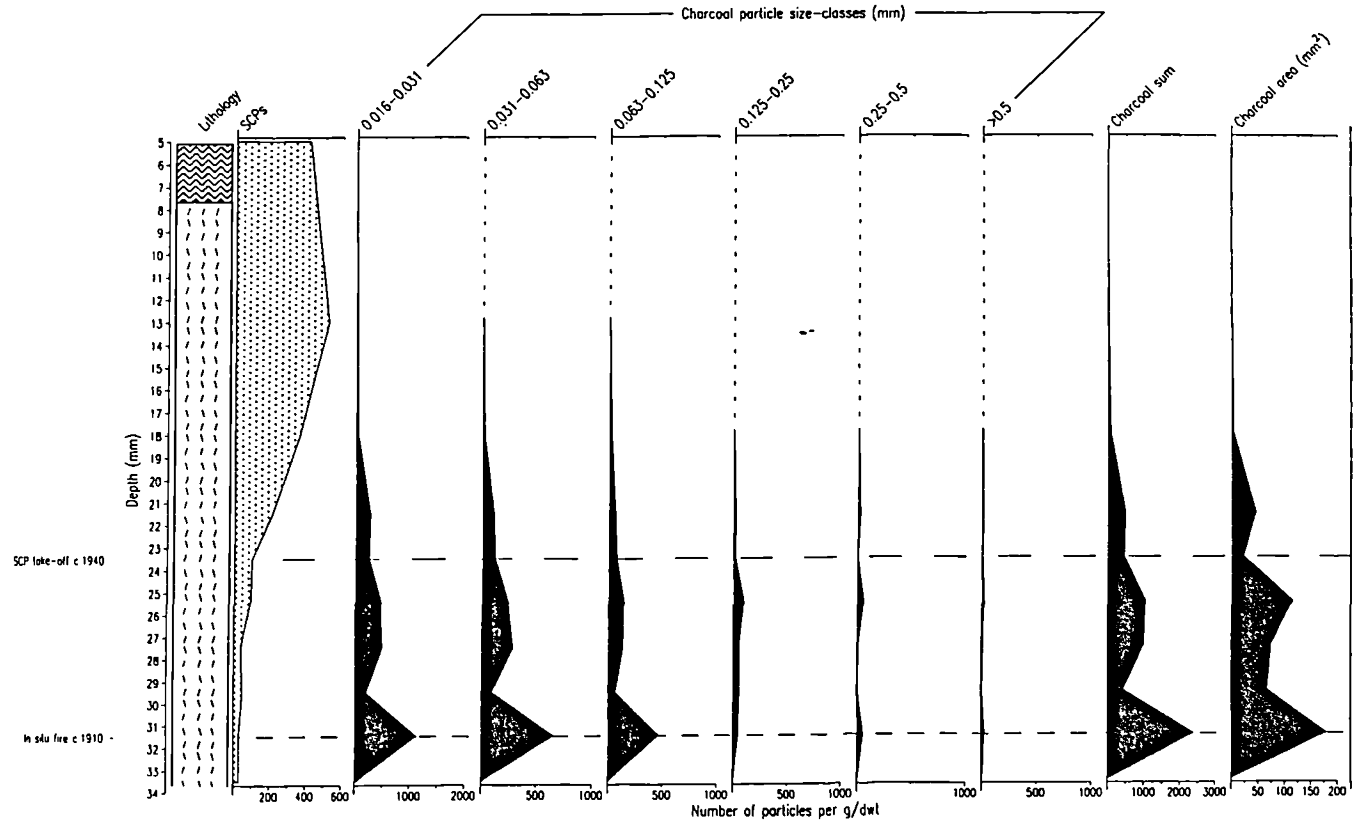
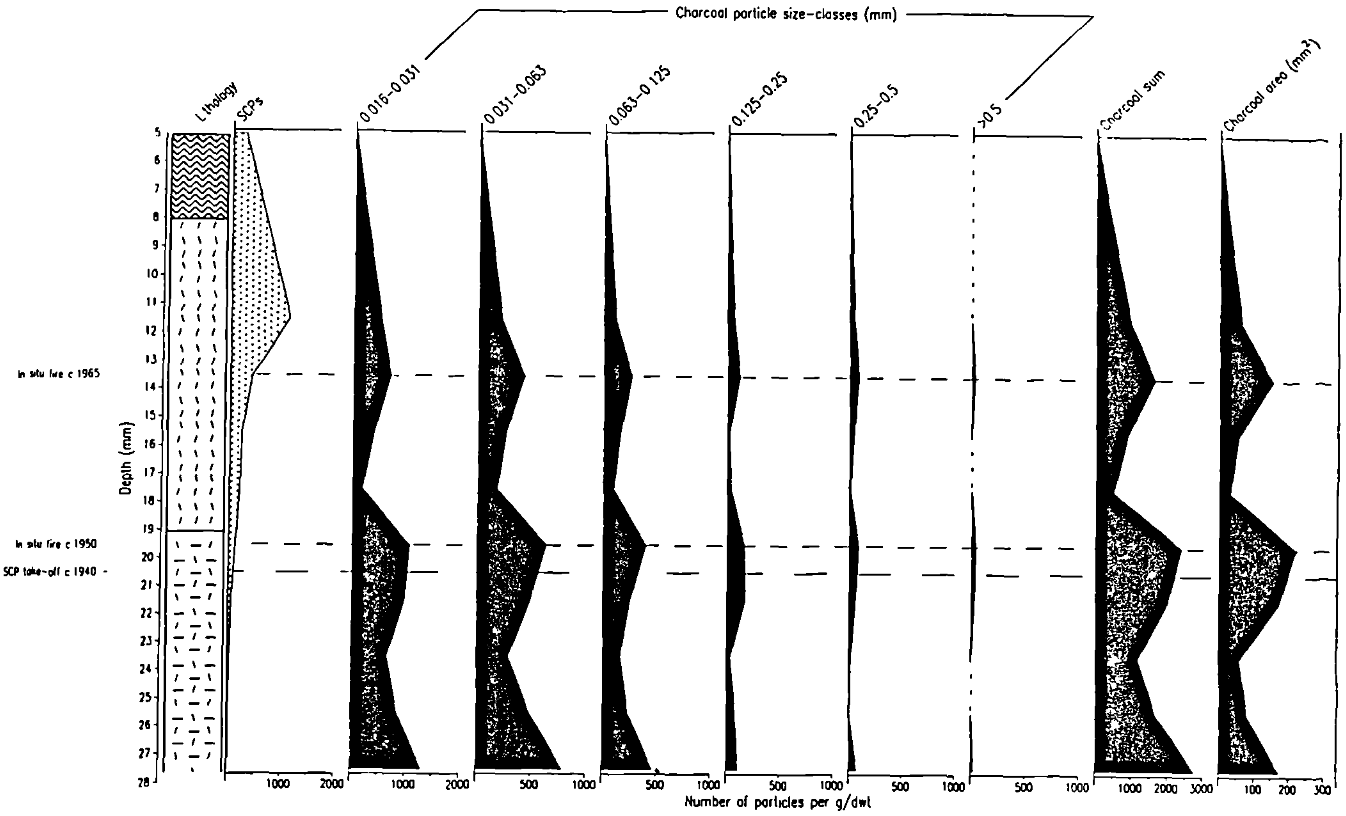


Figure 4.8: Charcoal profiles from the Tulach Hill mor humus soil cores *Tulach 11* and *Tulach 12*.

Tulach 11: Charcoal profile




Tulach 12: Charcoal profile

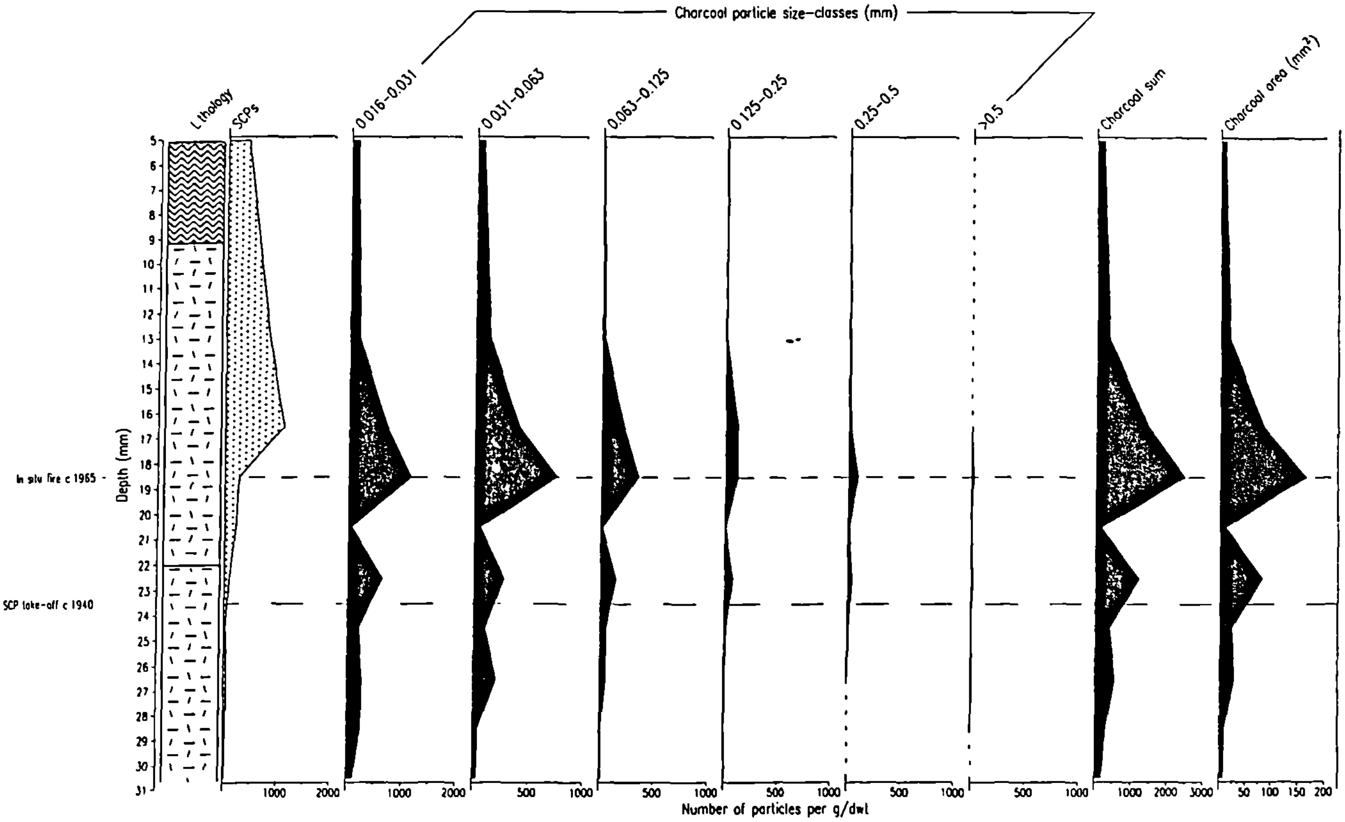
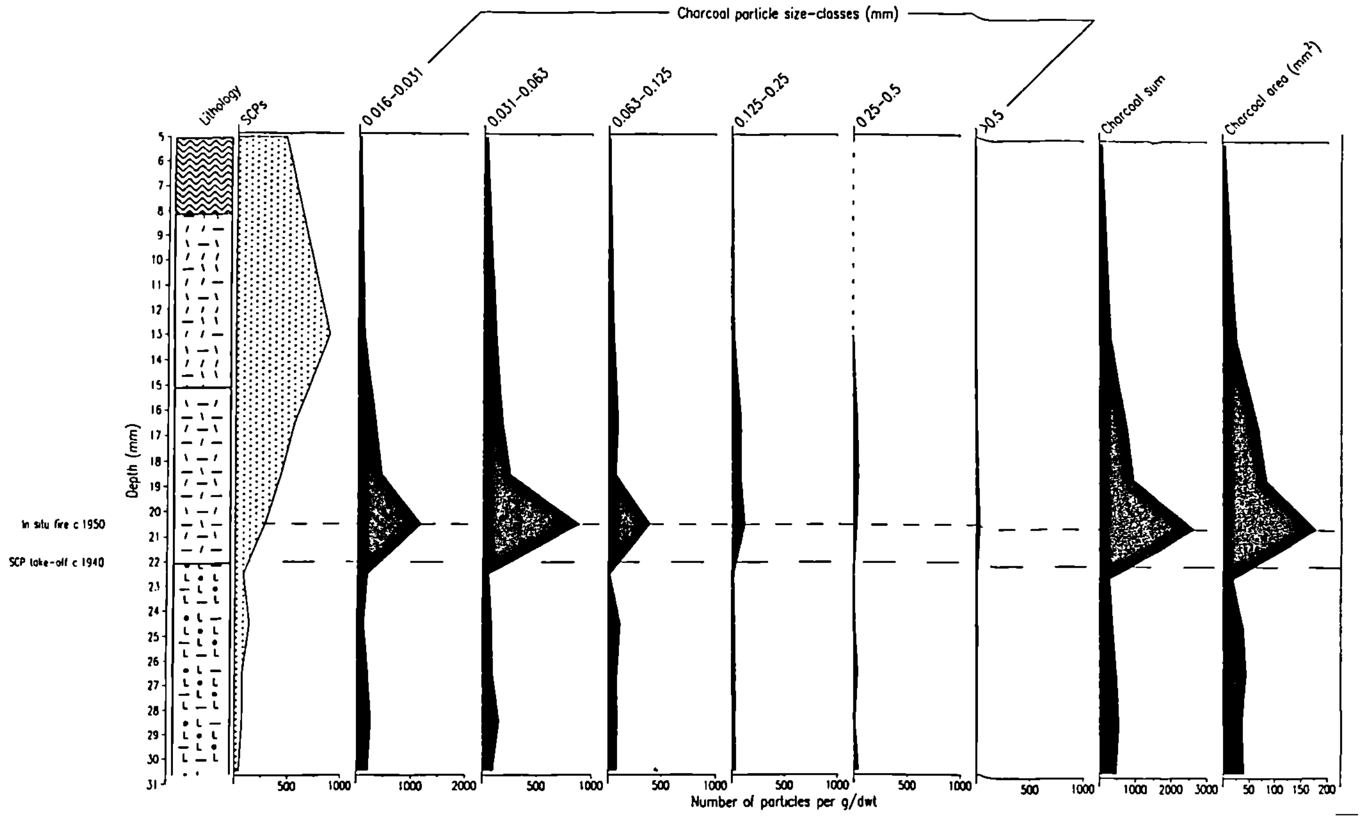


Figure 4.9: Charcoal profiles from the Tulach Hill mor humus soil cores *Tulach 13* and *Tulach 14*.

Tulach 13: Charcoal profile




Tulach 14: Charcoal profile

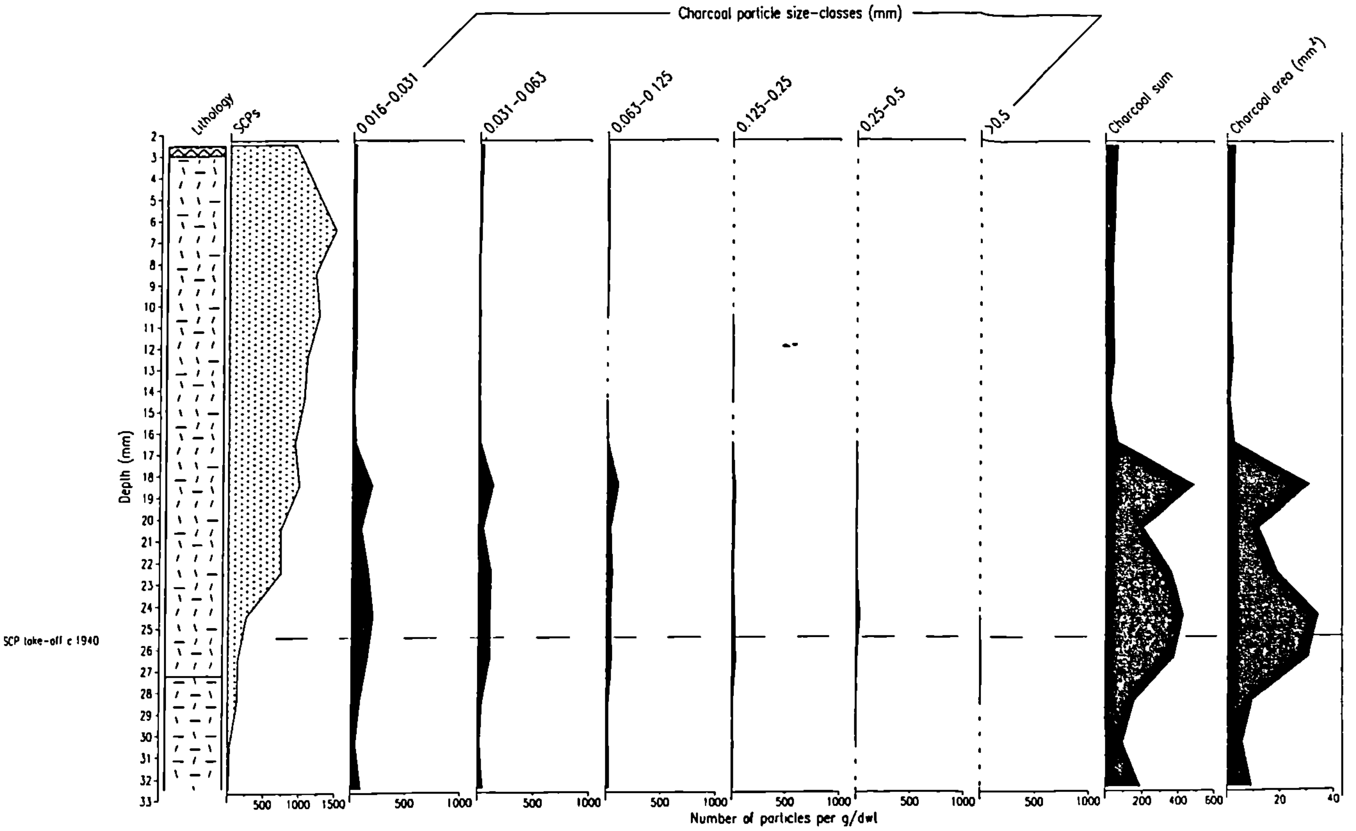
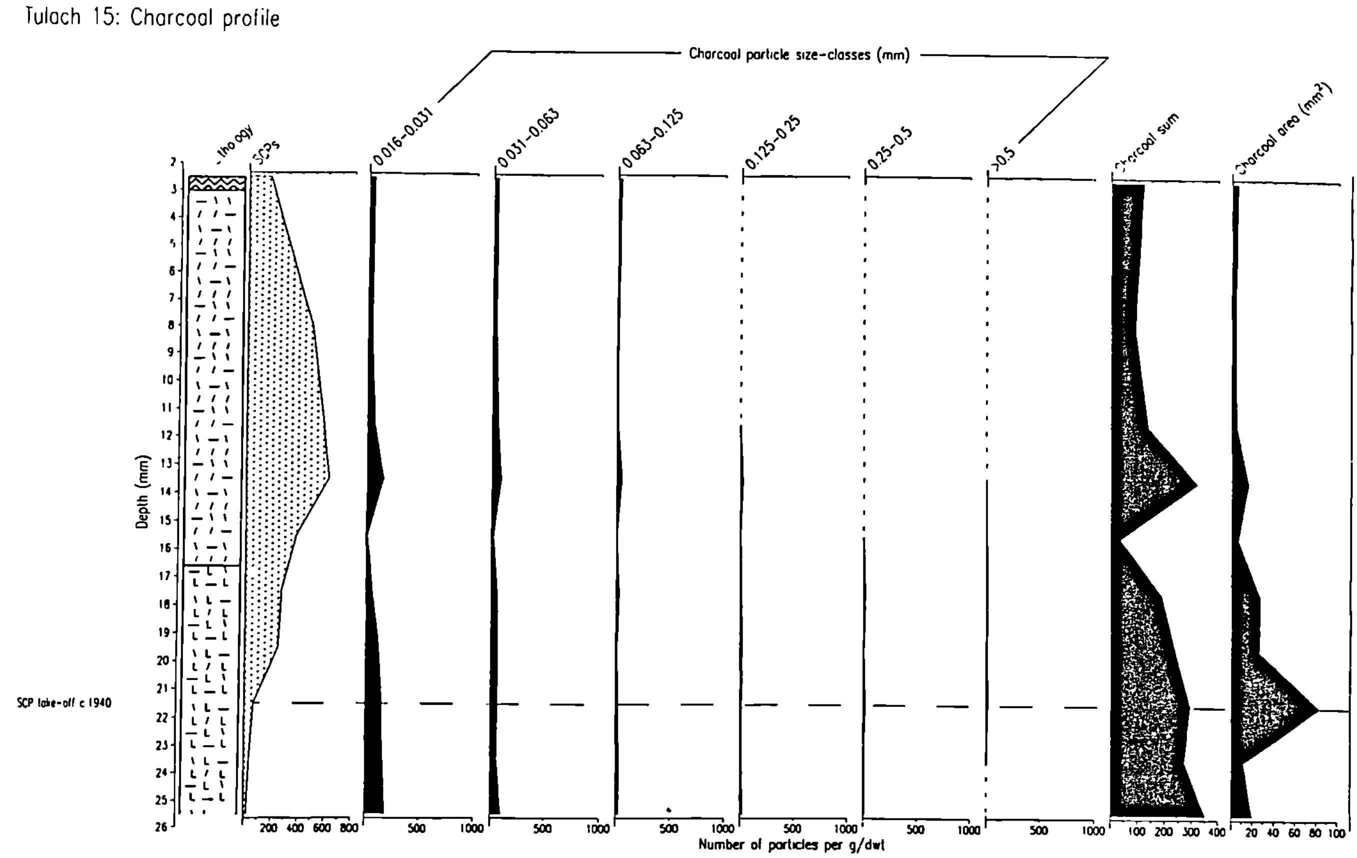
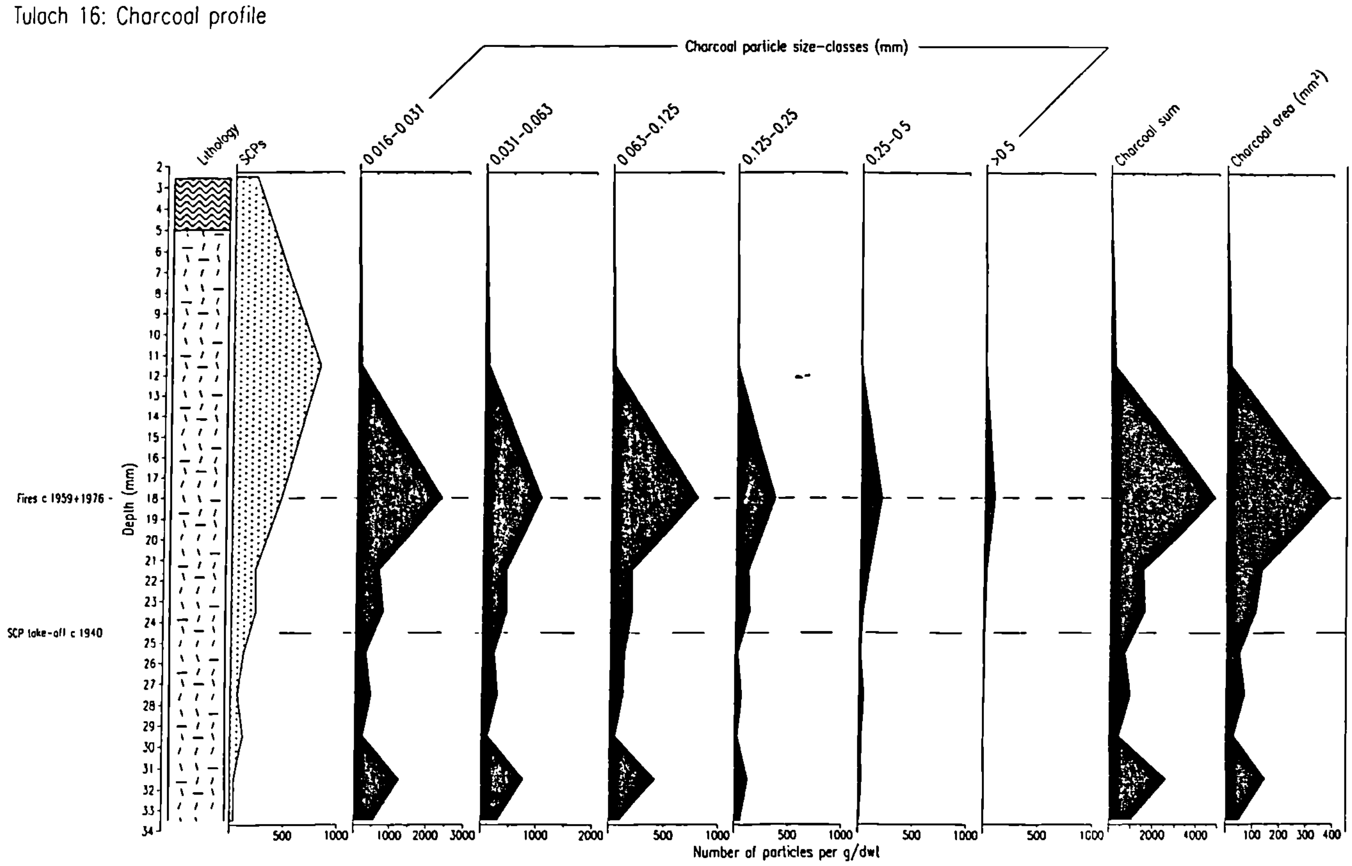


Figure 4.10: Charcoal profiles from the Tulach Hill mor humus soil cores *Tulach 15* and *Tulach 16*.



### 4.2.5 Discriminant analysis of charcoal assemblages from *in situ* and *ex situ* fires

Discriminant analysis is a powerful multivariate statistical technique used to characterise groups of samples on the basis of common quantitative variables. The linear combination of the variables, or discriminant function, which maximises the differences between the predetermined groups can be used to assign cases of unknown origin to a group (Davis, 1986; Klovan and Billings, 1967). At Tulach Hill discriminant analyses were used to determine whether fossil charcoal assemblages formed by *in situ* fires were significantly different from those derived from *ex situ* fires, on the basis of their particle size class structure. The discriminant functions produced were then used to classify charcoal assemblages of unknown origin from pre-AP sediments into either the *in situ* or *ex situ* categories.

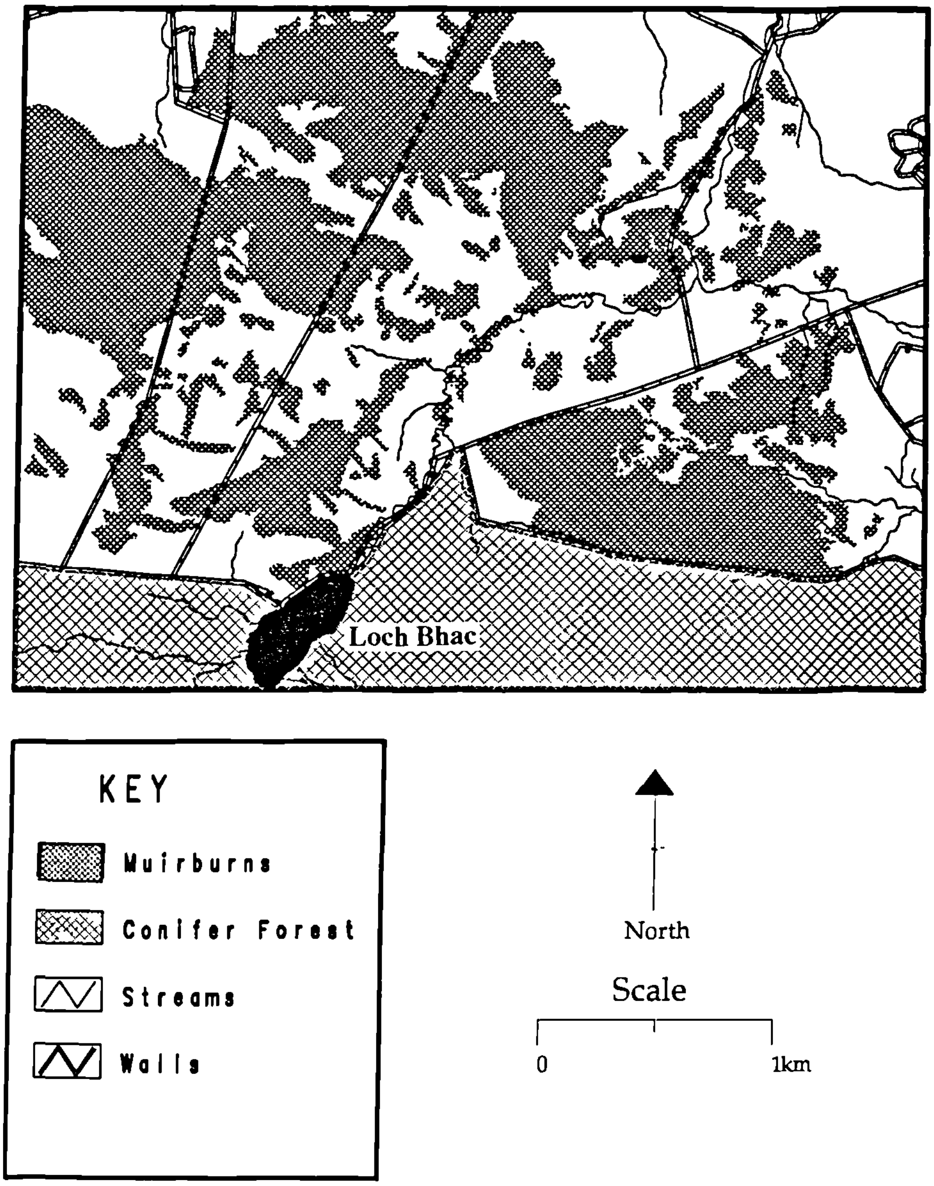
Seven *in situ* and sixty-one *ex situ* post-1950 sedimentary charcoal assemblages, identified from aerial photograph analyses, were used as the data set on which to calculate the discriminant function. Charcoal abundance in the assemblages was converted into an approximate particle influx so that samples from different cores could be compared. Influx values were calculated from dates interpolated from the SCP profiles by simple linear regression. A number of discriminant analyses were performed using different combinations of the six size classes as discriminatory variables to determine the combination of size class variables most effective at differentiating *in situ* assemblages from *ex situ* ones (Table 4.3). As the charcoal variables did not have multivariate normal distributions nonparametric nearest neighbour discriminant analyses were employed, prior probabilities of group membership were assumed to be equal. All discriminant analyses were performed using the computer statistics package SAS (SAS Institute Inc., 1985).

## 4.3 Results

### 4.3.1 Results of the AP analyses on Tulach Hill

Figures 4.1 and 4.2 provide summary maps of muirburn activity on Tulach Hill over the post-1940/50 period. Each AP holds a burning record of different duration, *i.e.* 9 years for the 1959 AP (1950-1959) but only 3 years for the 1988 AP (1985-1988). In an attempt to provide a more representative picture of annual patterns of fire activity approximate mean annual fire frequencies for the periods between adjacent APs were calculated, *i.e.* the numbers of burns on an AP divided by the number of years since the previous one (Table 4.1). Such an index only provides an approximate indication of gross changes in fire activity as it is unlikely that equal amounts of burning will have been carried out in each of the individual years between APs, and in some years no burning at all may have been conducted. The exact period of fire activity represented on the 1950 AP is indeterminable, though it is likely to hold a record of burning of between 7-13 years duration (Hester & Sydes, 1992). Figure 4.11 is a composite map produced by overlaying the individual muirburn maps and enables the identification of areas of the moor not burned at all during the post-1940/50 period.

Figure 4.11: The total area of Tulach Hill burned during the post-1940/50 period. Produced by overlaying the eight muirburn maps derived from aerial photographs.



Burning histories of every heather stand on the moor were determined by overlaying all of the possible combinations. The present day vegetation of Tulach Hill is a mosaic of heather patches with a wide spectrum of burning histories, vegetation stands with one hundred and twenty different burning histories were located (Stevenson *et al.*, 1995). Table 4.2 provides a shortened summary of how frequently areas of the moor were burned between *c.*1950 and 1988.

Table 4.1: Summary statistics for areas burned on Tulach Hill between the 1940s and 1988.

| Aerial photograph | No. of years burning represented | No. of new burns | No. of burns per year | Area burned (ha) | | % of whole moor burned | | Mean area per burn (ha) |
|---|---|---|---|---|---|---|---|---|
| | | | | Total | Per year | Total | Per year | |
| 1950 | 7 to 13* | 29 | - † | 92.14 | - † | 9.5 | - † | 3.18 |
| 1959 | 9 | 57 | 7.13 | 134.09 | 16.76 | 13.8 | 1.7 | 2.35 |
| 1965 | 6 | 52 | 8.67 | 87.81 | 14.64 | 9 | 1.5 | 1.69 |
| 1969 | 4 | 36 | 9.00 | 85.05 | 21.26 | 8.8 | 2.2 | 2.36 |
| 1976 | 7 | 37 | 5.29 | 69.90 | 9.98 | 7.2 | 1.0 | 1.89 |
| 1980 | 4 | 40 | 10.00 | 21.56 | 5.39 | 2.2 | 0.6 | 0.54 |
| 1985 | 5 | 42 | 8.40 | 85.35 | 17.07 | 8.8 | 1.8 | 2.03 |
| 1988 | 3 | 6 | 2.00 | 4.73 | 1.58 | 0.5 | 0.2 | 0.79 |
| Means | 5.63 | | 7.21 | | 16.06 | | 1.3 | 1.85 |

* The exact number of years muirburns represented on the 1950 AP is indeterminable but is likely to fall between 7 and 13 years (Hester & Sydes, 1992).
† As the exact number of years burning activity represented on the 1950 AP is not known mean figures cannot be calculated for these indices.

Levels of muirburn on Tulach Hill over the period studied were very low, on average less than 2% of the moor being burned annually (Table 4.1). Such low burning rates are far below the optimum of 10-15% prescribed Muirburn Working Party (1977) but are comparable with estimates derived for the Grampian and Border regions by Hester and Sydes (1992). As a consequence of the low burning rates approximately 56% of the moorland vegetation at Tulach Hill was not burned at all during the post-1940s period (Table 4.2 & Figure 4.11).

Table 4.2: Burn recurrence intervals for Tulach Hill over the 1940s-1988 period.

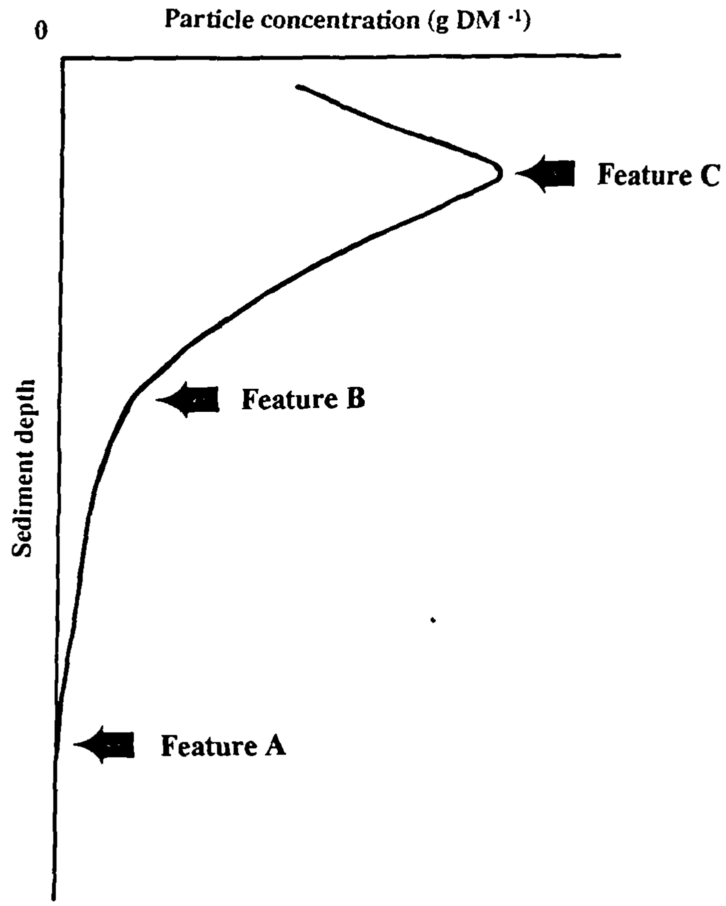
| Number of times burned post-1940s | Area of land burned (ha) | % of land area burned |
|---|---|---|
| 0 | 545 | 56 |
| 1 | 271 | 29 |
| 2 | 111 | 12 |
| 3 | 21 | 2 |
| 4 | 5 | 0.5 |
| 5 | 0.3 | 0.03 |
| 6 | 0.01 | 0.001 |

Patterns of muirburn varied greatly over the period studied (Figures 4.1 & 4.2), prior to 1950 a small number of large, wide patches were burned, between 1977-1980 an above average number (*c.*10 per year) of very small, thin muirburns were conducted, and between 1986-1988 only a restricted number of very small areas of the moor were burned. Throughout the rest of the period the numbers of fires conducted were relatively constant (7-9 per year) with a mixture of all sizes.

### 4.3.2 SCP profiles

The form of the SCP curves in the Tulach Hill soil profiles, on the left of Figures 4.3-4.10 & 4.13-4.15, reflect those commonly found in lake sediment cores (Figure 4.12) (*e.g.* Renberg & Wik, 1984; Renberg & Wik, 1985a & b; Rose, 1991; Rose *et al.*, 1995). Rose *et al.* (1995) suggest that three features of SCP profiles from UK and Irish sediment sequences can be used for dating purposes: A - the start of the SCP record which equates to the mid-nineteenth century; B - the rapid increase in SCP concentration between the 1940s-1970s; and C - the sub-surface peak in SCP concentration dated to the late-1970s to early-1980s (Figure 4.12). The utility of these features in the mor humus soil cores studied is discussed in Section 4.4.2.

Figure 4.12: Schematic spherical carbonaceous particle profile showing the three dating features referred to in the text. (Redrawn from Rose *et al.* (1995))



### 4.3.3 Fire histories reconstructed using charcoal analyses

#### 4.3.3.1 The Tulach Hill fire histories

The fire histories of the sixteen locations on Tulach Hill reconstructed by charcoal analysis are presented in Figures 4.3-4.10. The charcoal data are displayed in several formats: size class distribution across six geometrically progressive size classes; charcoal sum (*i.e.* the sum of particles in all size classes); and charcoal area (*i.e.* the sum over size classes of the product of mean particle area and particle number). All measures are expressed per gram dry weight of sediment. A key for the lithologies on the left of the charcoal diagrams can be found in Appendix 3 (Troels-Smith, 1955).

Despite the relatively low accumulation rates of the mor humus soils (Table 4.7), clear and differentiable patterns of charcoal abundance exist in the sediment records and the resolution is sufficient in most instances for individual fires to be discernible. The majority of known post-1950 *in situ* fire events are readily identifiable in the charcoal diagrams, represented by marked increases of charcoal particle abundance in all six size classes, the charcoal sum and the total area index (*e.g.* 21-22 mm in *Tulach 1* & 9-10 mm in *Tulach 4*). The known *in situ* fire event in core *Tulach 11* is not, however, so obvious. It is marked by increases in charcoal abundance across the range of indices but it is not so obvious that it is are immediately recognisable as the product of an *in situ* fire event, a feature which could lead to potential problems of interpretation.

Two cores, *Tulach 11* & *Tulach 16*, were taken from locations burned twice during the post-1950 period, in *Tulach 11* both fire events are discernible (at depths of 13-14 and 19-20 mm respectively). However, in *Tulach 16* the sampling resolution was too coarse for the two fire events to be differentiated and they are represented by a single peak in charcoal abundance between at 16-20 mm. Cores taken from locations not burned in the post-1950 period have very low quantities of charcoal in their upper profiles, despite the fact that most of the cores were taken from positions <60 m (some as close as 10-20 m) from known fires during this period, suggesting that charcoal dispersal from the muirburns on Tulach Hill was very limited (Chapter 5).

#### 4.3.3.2 Discriminant analyses of the Tulach Hill charcoal data.

Table 4.3 summarises the performance of the various combinations of the six charcoal size class variables at discriminating charcoal assemblages produced by *in situ* and *ex situ* fires.

The percentages of assemblages correctly classified and the squared differences between groups represent measures of the effectiveness of each of the discriminant analyses (Gauch, 1982; Klovan & Billings, 1967).

Table 4.3: The relative performance of discriminant analyses conducted to discriminate charcoal assemblages produced by *in situ* and *ex situ* fires using different combinations of the six charcoal size classes as discriminatory variables.

| Charcoal size classes used as discriminant variables | Proportion of assemblages correctly classified | Squared distance between groups |
|---|---|---|
| ABCDEF | 0.985 | 22.12 |
| ACDEF | 0.985 | 22.07 |
| ABCDE | 0.985 | 21.68 |
| BCDEF | 0.985 | 21.24 |
| BCDE | 0.985 | 21.02 |
| CDE | 0.985 | 20.32 |
| ABCEF | 0.985 | 16.12 |
| BCE | 0.971 | 13.08 |
| CE | 0.971 | 12.26 |
| BE | 0.971 | 11.65 |
| AE | 0.971 | 11.62 |
| DE | 0.971 | 11.58 |
| E | 0.971 | 11.57 |
| ADCDF | 0.956 | 16.64 |
| ABDEF | 0.956 | 15.34 |
| BCD | 0.956 | 15.06 |
| CD | 0.956 | 14.73 |
| EF | 0.956 | 12.12 |
| CF | 0.941 | 12.19 |
| BF | 0.941 | 10.84 |
| AC | 0.941 | 10.42 |
| BC | 0.941 | 10.41 |
| C | 0.941 | 10.41 |
| DF | 0.926 | 10.16 |
| AF | 0.926 | 9.81 |
| F | 0.926 | 7.42 |
| B | 0.912 | 9.59 |
| A | 0.912 | 8.52 |
| D | 0.912 | 7.54 |

Key to size class variables:

A = 16-31 μm B = 31-63 μm C = 63-125 μm
D = 125-250 μm E = 250-500 μm F = > 500 μm

The discriminant function calculated using all six charcoal size classes as discriminatory variables was most effective, the full results of this analysis are presented below in the 'confusion table' (Table 4.4).

Table 4.4: Results of the discriminant analysis of *in situ* and *ex situ* charcoal assemblages using all six of the size classes as discriminatory variables.

| Actual group | No. of charcoal assemblages | Predicted group membership *In situ* | Predicted group membership *Ex situ* |
|---|---|---|---|
| *In situ* assemblage | 7 | 7<br>100% | 0<br>0% |
| *Ex situ* assemblage | 61 | 1<br>1.64% | 60<br>98.36% |
| Percentage of 'grouped' assemblages correctly classified: 98.53% | | | |

All of the *in situ* assemblages were correctly classified and only one *ex situ* charcoal assemblage was wrongly classified, *i.e.* as having the characteristics similar to those of an *in situ* assemblage. This indicates that in the majority of cases the size class distributions of the charcoal assemblages derived from *in situ* fires are notably different those of *ex situ* fire events. Interestingly the *ex situ* assemblage wrongly classified as an *in situ* assemblage was produced by a fire event >50 m away from the deposition site, whilst charcoal assemblages derived from much more local fires, as little as 10 m away, were correctly classified as *ex situ* assemblages.

The majority of the charcoal assemblages produced by *in situ* fires are notable in the charcoal diagrams by obvious peaks in total particle abundance, *e.g.* at 22 mm depth in *Tulach 1* and 9 mm depth in *Tulach 4* respectively. For this reason a further discriminant analysis was performed on the *in situ* / *ex situ* charcoal assemblage data set with the total charcoal sum as the only discriminatory variable in order to determine whether charcoal assemblages could be differentiated on this basis alone. If the total charcoal sum were as equally effective at distinguishing *in situ* from *ex situ* fires as the size class distribution a significant amount of analysis time could be saved over counting the charcoal particles into size classes.

Table 4.5: Results of the discriminant analysis with total charcoal sum as the only discriminatory variable.

| | | Predicted group membership | |
|---|---|---|---|
| Actual group | No. of charcoal assemblages | *In situ* | *Ex situ* |
| *In situ* assemblage | 7 | 7<br>100% | 0<br>0% |
| *Ex situ* assemblage | 61 | 7<br>11.48% | 54<br>88.52% |
| Percentage of 'grouped' assemblages correctly classified: 89.71% | | | |

Table 4.5 presents the results of the discriminant analysis using total charcoal abundance as the lone discriminatory variable. Almost ninety percent of the samples were correctly classified, including all of the *in situ* assemblages, however, discrimination by total charcoal sum alone is not as effective as using the size class information (98.53% correct classification).

#### 4.3.3.3 Classification of pre-1950 fire events.

The linear discriminant function, derived from all six size class variables, was used to classify charcoal assemblages from the Tulach Hill soil cores pre-dating aerial photograph records of fire activity. Twenty-three charcoal assemblages, those believed most likely to represent *in situ* or nearby fires because of their prominent nature in the charcoal profiles, were selected and classified using the discriminant function. The results of the classification exercise are displayed below in Table 4.6.

Table 4.6: Results of the classification of suspected *in situ* fire events by the Tulach Hill discriminant function.

| Core | Sample depth (mm) | Group classified into | Posterior probability of group membership |
|---|---|---|---|
| *Tulach 2* | 37-38 | *In situ* | 81.33% |
| *Tulach 2* | 43-44 | *In situ* | 81.33% |
| *Tulach 2* | 53-54 | *In situ* | 81.33% |
| *Tulach 3* | 25-26 | *In situ* | 100.00% |
| *Tulach 3* | 33-34 | *In situ* | 81.33% |
| *Tulach 3* | 37-38 | *Ex situ* | 100.00% |
| *Tulach 5* | 23-24 | *Ex situ* | 100.00% |
| *Tulach 5* | 33-34 | *Ex situ* | 100.00% |
| *Tulach 5* | 43-44 | *Ex situ* | 100.00% |
| *Tulach 5* | 51-52 | *Ex situ* | 100.00% |
| *Tulach 5* | 55-56 | *Ex situ* | 100.00% |
| *Tulach 5* | 61-62 | *Ex situ* | 100.00% |
| *Tulach 6* | 15-16 | *Ex situ* | 100.00% |
| *Tulach 7* | 16-17 | *Ex situ* | 100.00% |
| *Tulach 7* | 18-19 | *Ex situ* | 100.00% |
| *Tulach 7* | 20-21 | *In situ* | 94.57% |
| *Tulach 8* | 24-25 | *Ex situ* | 100.00% |
| *Tulach 8* | 26-27 | *Ex situ* | 100.00% |
| *Tulach 9* | 33-34 | *In situ* | 81.33% |
| *Tulach 9* | 37-38 | *In situ* | 81.33% |
| *Tulach 10* | 27-28 | *Ex situ* | 100.00% |
| *Tulach 10* | 31-32 | *In situ* | 81.33% |
| *Tulach 11* | 27-28 | *Ex situ* | 100.00% |

Nine of the twenty-three suspected *in situ* charcoal assemblages were actually classified as *in situ* fire events by the discriminant function. The majority of the assemblages which were classified as being the product of *in situ* fires are represented in the charcoal profiles by pronounced peaks in charcoal abundance, confirming subjective interpretations. A number of less pronounced charcoal assemblages, however, which would not necessarily have been identified subjectively as *in situ* assemblages (*e.g.* 43-44 and 53-54 mm depth in *Tulach 2*), were also classified as having *in situ* origins. Alternatively, the prominent peak at a depth of 33-34 mm depth in *Tulach 5* was not classified as an *in situ* fire event, whilst by eye alone an analysts may well have interpreted this assemblage as the product of an *in situ* fire event. The consistently high posterior probabilities of classification (>81.33% in all cases), an estimate of how likely correct membership of the predicted group is, suggest that classification of unknown samples is relatively reliable (Klovan & Billings, 1967; Gauch, 1982).

The stratigraphic features of the fire histories from the sixteen Tulach Hill cores, determined by the various methods described above, are summarised in Table 4.7. The approximate chronologies of the cores were estimated by extrapolation and interpolation from the SCP records using simple linear regression methods, assuming constant accumulation rates and no hiatuses. It is acknowledged that such an approach makes a number of implicit assumptions, the most important being that accumulation rates have been constant over time. The isochrones available from the SCP profiles (Section 4.4.2), the positions of the known post-1950 fires which fit well in to the interpolated chronologies and the homogeneous nature of the mor humus soil profiles do however suggest that the method adopted is relatively accurate.

Table 4.7: Summary of the stratigraphic features in the charcoal profiles from the sixteen Tulach Hill cores.

| Core | Core length (mm) | SCP take-off (mm) | Post-1940 accumulation rate (mm/yr) | Age of core base | Post-1950 *in situ* fires | Distance from nearest post-1950 fire | Pre-1950 in situ fires[b] |
|---|---|---|---|---|---|---|---|
| **Tulach 1** | 75.5 | 22.5 | 0.42 | c.1810 | 1 (1950[a]) | 50 m (1965) | None |
| **Tulach 2** | 73.5 | 32.5 | 0.61 | c.1870 | None | 50 m (1950) | 3 |
| **Tulach 3** | 65.5 | 20.5 | 0.39 | *c.*1820 | None | 60 m (1950) | 2 |
| **Tulach 4** | 63.5 | 18.5 | 0.35 | *c.*1810 | 1 (1976) | 90 m (1976) | None |
| **Tulach 5** | 67.5 | 20.5 | 0.39 | *c.*1820 | None | 60 m (1950) | None |
| **Tulach 6** | 21.5 | 12.5 | 0.24 | *c.*1900 | None | 10 m (1950) | None |
| **Tulach 7** | 28.5 | 15.5 | 0.29 | *c.*1900 | None | 40 m (1950) | 1 |
| **Tulach 8** | 30.5 | 23.5 | 0.44 | *c.*1920 | None | 20 m (1950) | None |
| **Tulach 9** | 43.5 | 28.5 | 0.54 | *c.*1910 | None | 45 m (1950) | 2 |
| **Tulach 10** | 33.5 | 22.5 | 0.42 | *c.*1910 | None | 50 m (1985) | 1 |
| **Tulach 11** | 27.5 | 20.5 | 0.39 | *c.*1920 | 2 (1950 & 1965) | 90 m (1976) | None |
| **Tulach 12** | 30.5 | 23.5 | 0.44 | *c.*1920 | 1 (1965) | 20 m (1950) | None |
| **Tulach 13** | 30.5 | 21.5 | 0.41 | *c.*1915 | 1 (1950) | 30 m (1965) | None |
| **Tulach 14** | 32.5 | 25.5 | 0.48 | *c.*1910 | None | 20 m (1965) | None |
| **Tulach 15** | 25.5 | 20.5 | 0.39 | *c.*1925 | None | 40 m (1965) | None |
| **Tulach 16** | 33.5 | 24.5 | 0.46 | *c.*1920 | 2 (1959 & 1976) | 20 m (1950) | None |

[a] Date of aerial photograph on which fire identified

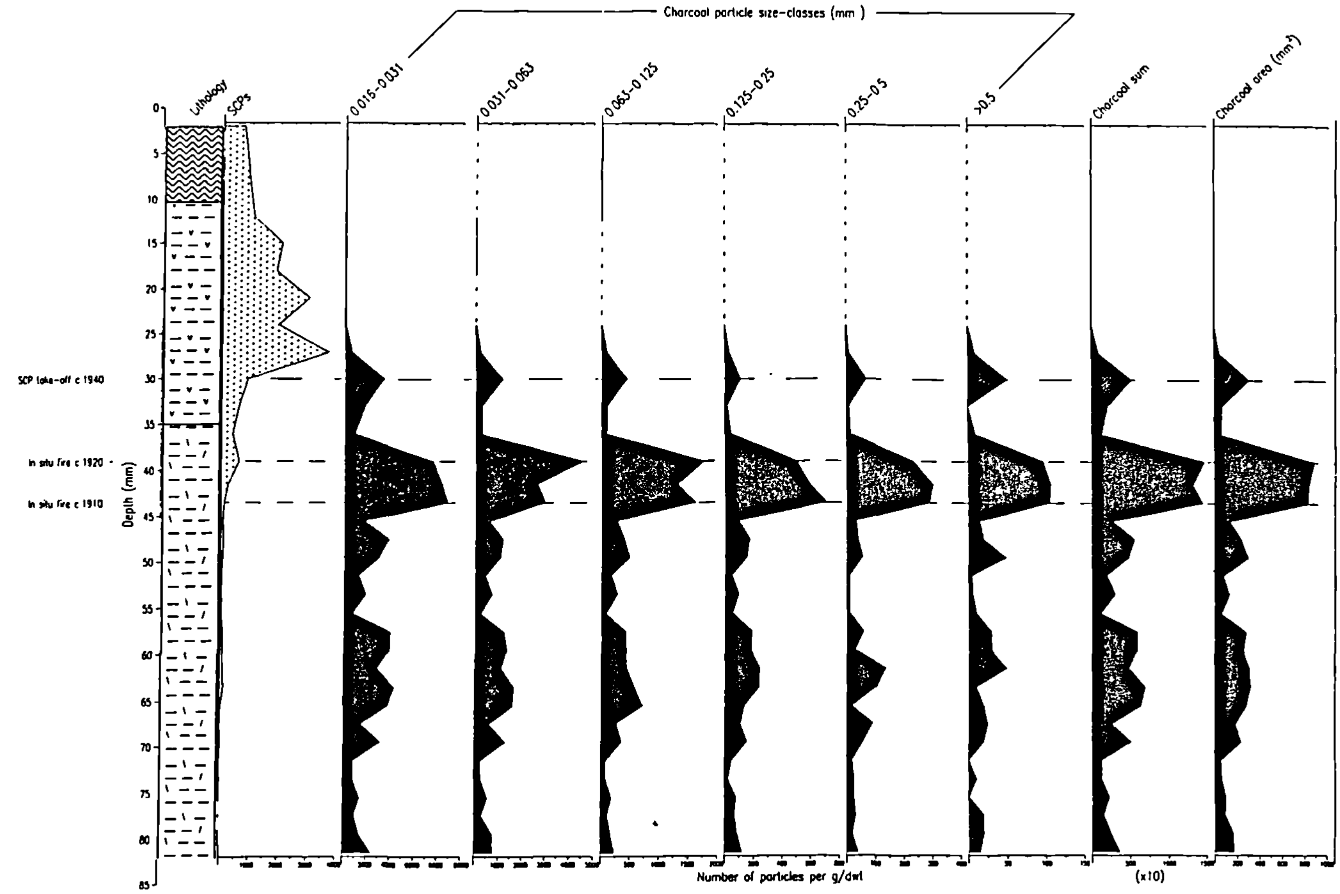
[b] See Table 4.6

### 4.3.4 Burning histories of old heather stands from five additional Perthshire moors.

The Auldallan Hill, Blacklaw Hill, Gallow Hill and Trochry Hill cores (Figures 4.13-4.15) all have very low post-1940 charcoal levels confirming that the core locations were not

Figure 4.13: Charcoal profiles from the Auldallan Hill and Blacklaw Hill mor humus soil cores.

Auldallan Hill: Charcoal profile




Blacklaw Hill: Charcoal profile

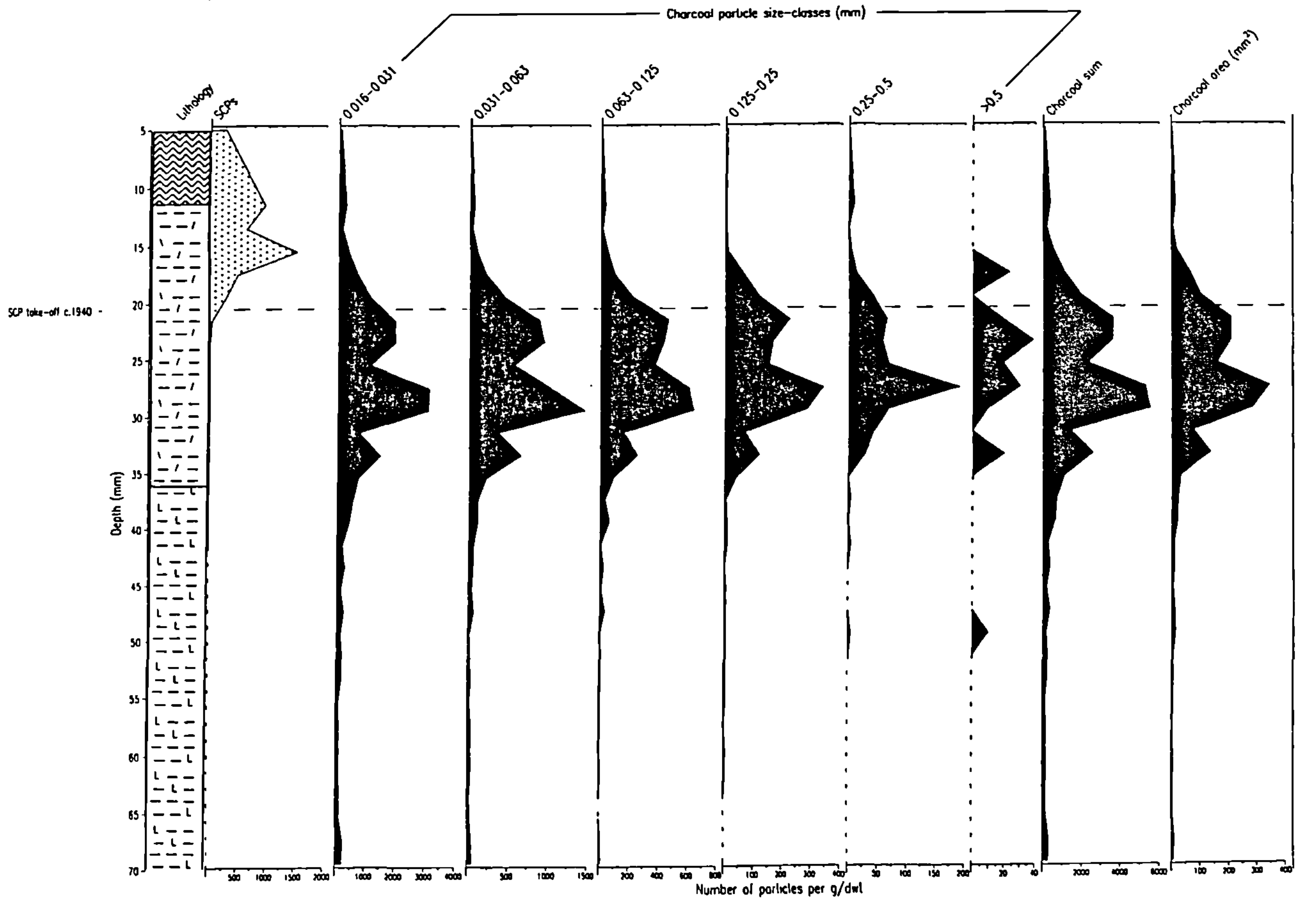
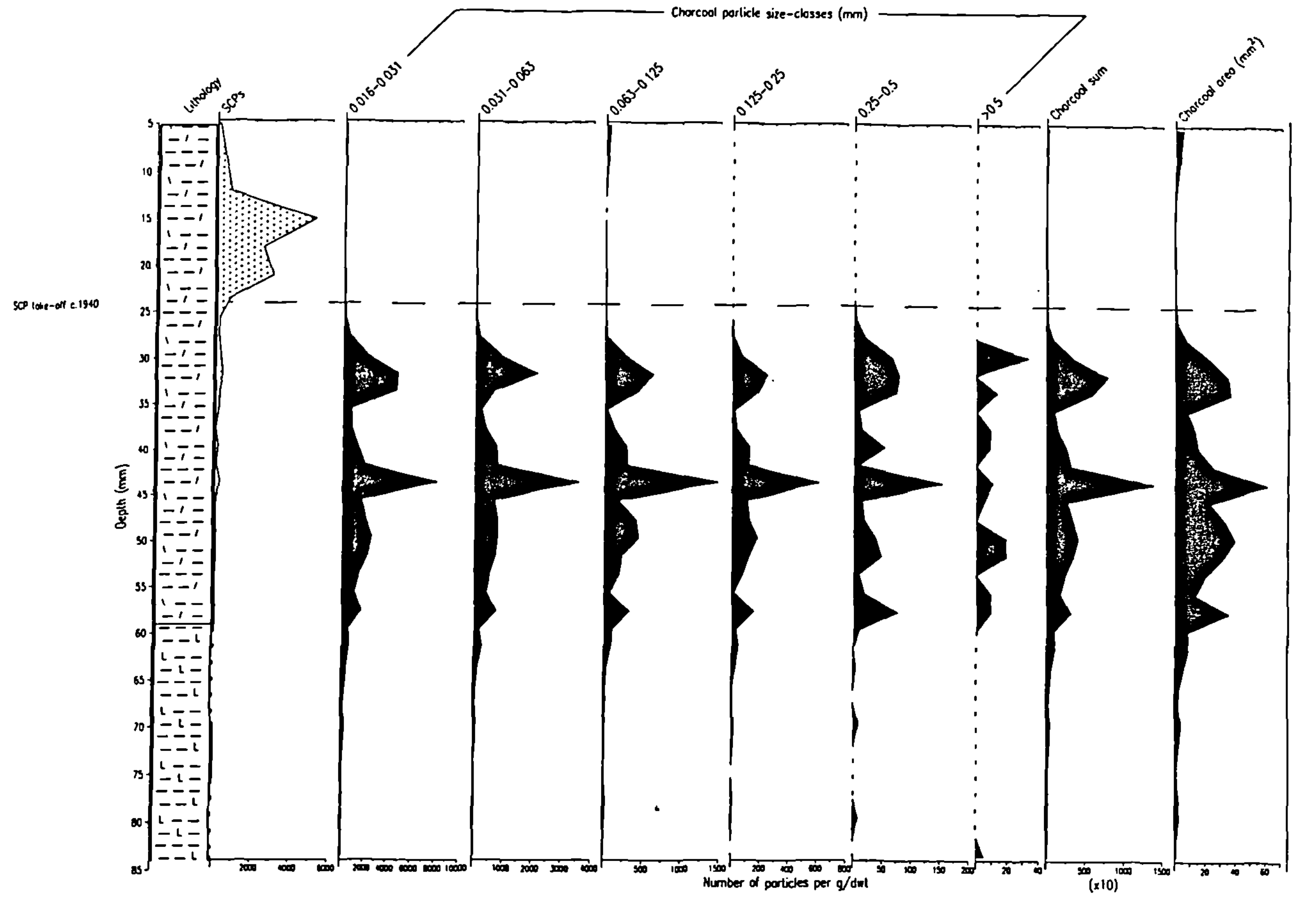


Figure 4.14: Charcoal profiles from the Gallow Hill and Trochry Hill mor humus soil cores.

Gallow Hill: Charcoal profile




Trochry Hill. Charcoal profile

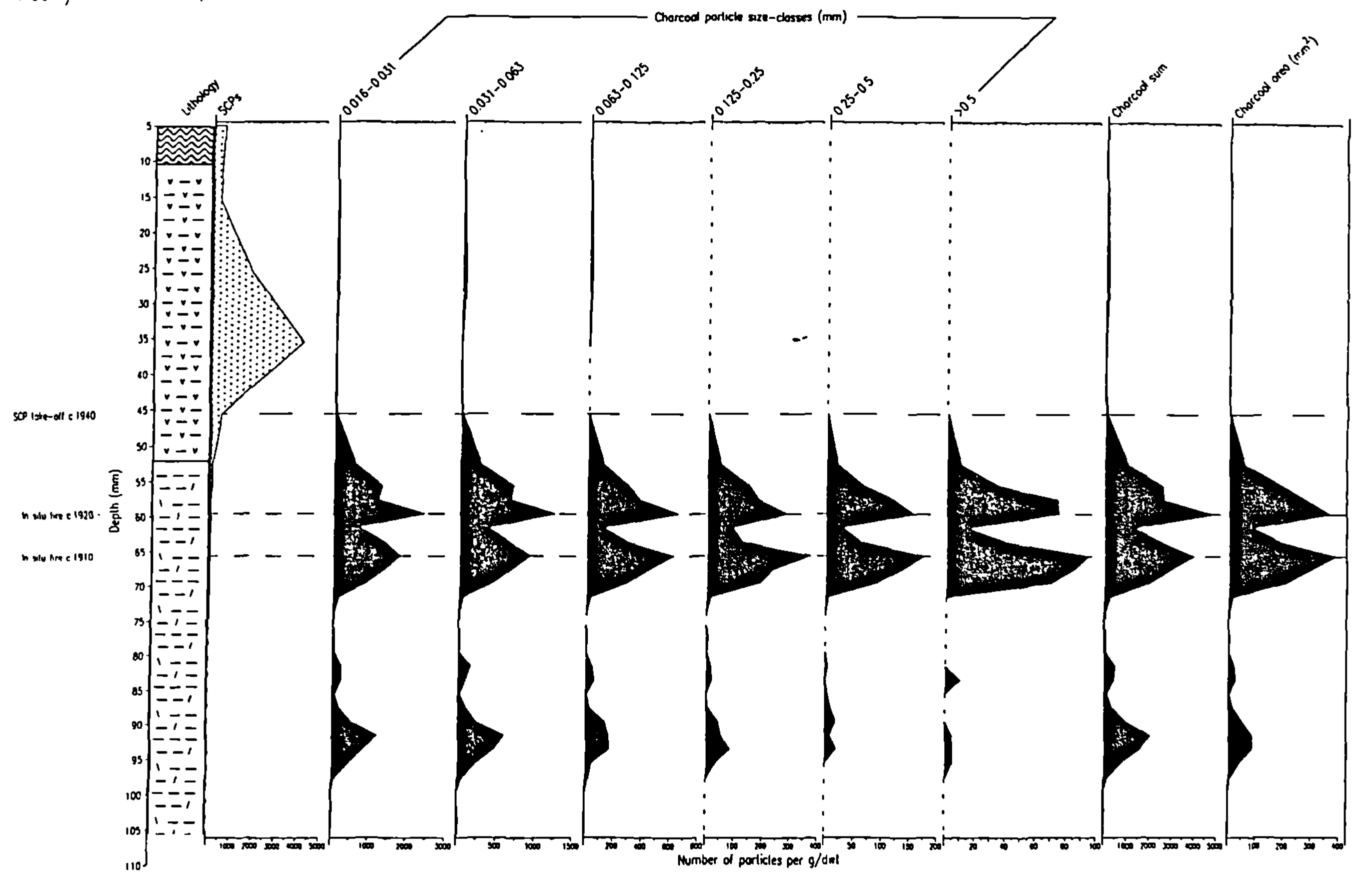
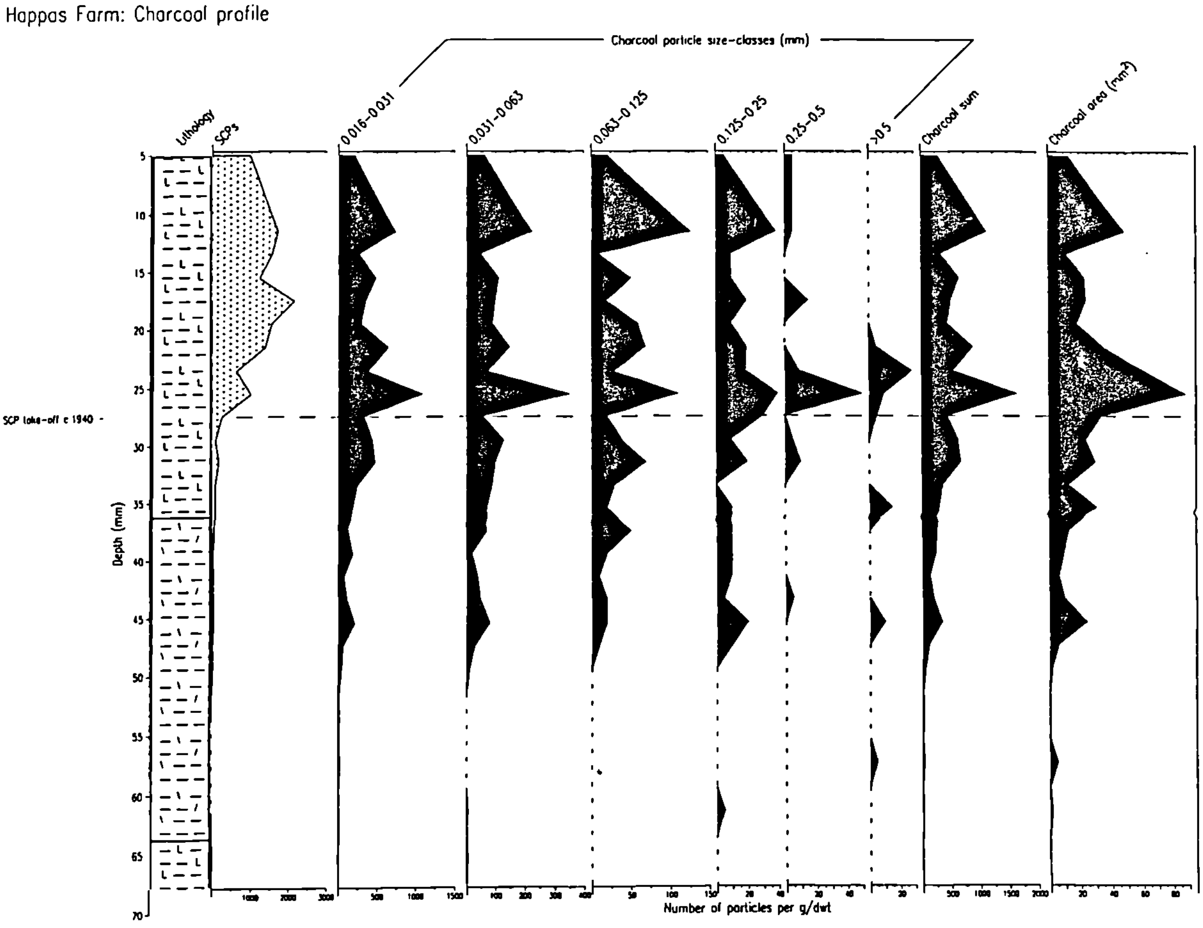


Figure 4.15: Charcoal profile from the Happas Farm mor humus soil core.



burned during the period. At Happas Farm, however, more variable charcoal levels throughout the post-1940 period suggest local fire activity may have occurred. Subsequent AP analyses, of APs not included in the original analysis conducted by Kirkpatrick (1992), however, confirm that a number of burns had been set very close to the site during this period but no *in situ* fires had occurred.

The interpretation of these charcoal profiles proved somewhat problematic as in several of them it was not immediately obvious which charcoal assemblages were definitely the product of *in situ* and *ex situ* fire events. As the analyses of the Tulach Hill profiles demonstrate not all *in situ* and *ex situ* charcoal assemblages can be categorically differentiated by eye alone, or at least not without detailed study. The discriminant function developed at Tulach Hill could not realistically be used to classify the charcoal assemblages from these sites in order to aid differentiation of them, despite the similarities in soil characteristics. The following interpretations of fire activity at the sites are, therefore, based on subjective interpretations only, using the knowledge gained from the Tulach Hill cores.

**Auldallan Hill -** The known lack of *in situ* fires in the post-1940 period is a reflected by very low sedimentary charcoal levels. The last *in situ* fires at the site, inferred from the prominent peaks in charcoal abundance between 38-40 and 40-42 mm, are estimated to have occurred *c.*1920 and *c.*1910 respectively. Average charcoal abundance pre-1940 is much greater than in the post-1940 period perhaps suggesting generally higher levels of local burning activity.

**Blacklaw Hill -** Very low charcoal abundance in the post-1940 sediment reflect the known absence of *in situ* fires. The prominent charcoal peak between 27-29 mm (c.1910) is suspected to represent the last *in situ* fire event on the site. The less prominent charcoal assemblages at 21-23 and 33-34 mm are believed to be the product of *ex situ* fires. Average charcoal abundance pre-1940 is much greater than in the post-1940 period perhaps suggesting a generally higher intensity of local fire activity.

**Gallow Hill -** An almost total absence of charcoal in the upper 30 mm of the core reflects the lack of post-1940 nearby and *in situ* fire activity. The charcoal peak at 43-44 mm is particularly marked and is assigned an *in situ* origin. The slightly less obvious assemblage at 31-34 mm could possibly be the product of an *in situ* fire, however, it is thought that it is more likely to represent a nearby *ex situ* fire. This location is, therefore, believed to have been last burned *c.*1900. Again average charcoal abundance pre-1940 is much greater than in the post-1940 period suggesting possibly higher levels of local fire activity.

**Trochry Hill -** The known absence of *in situ* burning during the post-1940 period is reflected by the very low charcoal abundance above 45 mm depth. The two prominent peaks in charcoal abundance, at 59-60 and 65-66 mm, are interpreted as the product of *in situ* fire events dating to approximately *c.*1920 and *c.*1910-1915 respectively. Average charcoal abundance pre-1940 is much greater than in the post-1940 period suggesting a generally higher intensity of local burning activity.

**Happas Farm -** On first inspection the post-c.1940 sediment record of the Happas Farm core appears to contain considerable quantities of charcoal, however, when studied more closely charcoal concentrations are low (<1600 particles per g/dwt of sediment). Such low quantities of charcoal throughout this period are believed to reflect fallout from nearby, but not *in situ,* fires. This location on Happas Hill has not been burned since *c.*1860, the approximate period covered by the core.

## 4.4 Discussion & conclusions

### 4.4.1 Aerial photograph analyses

Analyses of aerial photographs (APs) have been used previously in studies of vegetation and more specifically studies of moorland muirburn (*e.g.* Hester and Sydes 1992; Hunting Surveys and Consultants Ltd, 1986; Kirkpatrick, 1992; National Countryside Monitoring Scheme, 1988; Nature Conservancy Council, 1990). APs provide an excellent means of reconstructing histories of recent fire activity in the landscape, providing not only temporal histories of fire activity but the exact areal extent of fires. Aerial photographs are particularly useful in moorland contexts because the areas of vegetation burned are generally small and large numbers can be discerned and mapped on individual photographs.

The main constraint on using APs for reconstructing moorland fire histories is that a comprehensive time series of photographs is available for the study area so that fires are not missed in the periods between coverages. Ideally the time periods between photographs should not exceed approximately seven years, the length of time over which all muirburns remain visible on APs (Hester & Sydes, 1992). When the intervals between photographs consistently exceed seven years doubt must be cast upon the reliability of the fire history derived.

The use of the GIS system ARC/INFO to capture and collate the spatial data from the APs of Tulach Hill proved extremely effective providing results of an unprecedented degree of accuracy, far superior to less sophisticated methods involving the tracing and overlaying of muirburn patterns on acetate. The results from Tulach Hill reveal a remarkable degree of local heterogeneity in fire history, a feature which has not been reported before for Scottish heathland vegetation. Despite only approximately 1-2% of the moor being burned annually, and approximately 56% of the vegetation on the moor not having been burned for at least forty/fifty years, vegetation stands with one hundred and twenty different burning histories were identified (Appendix 4). Some small patches of present day vegetation had been burned up to six times in the 40-50 year period covered by this study. This aspect of heterogeneity of vegetation composition even on moors burned relatively infrequently perhaps deserves further investigation.

The potential of using APs for reconstructing histories of muirburn in moorlands has been shown to be excellent, and they should not be overlooked in other environmental contexts where temporal and spatial patterns of fire activity need to be mapped. Charcoal analyses of sediment sequences provide both a complementary and an alternative method of reconstructing fire histories which are of particular benefit beyond the time scale of aerial photographs. However, wherever possible when reconstructing recent fire histories for the post-1940/50 period AP analyses should perhaps be used in preference to charcoal analyses because they provide not only a record of the temporal frequency of fire but also the spatial extent of individual fire events which cannot be gained from charcoal analyses.

### 4.4.2 Spherical carbonaceous particles

Spherical carbonaceous particles (SCP) have not been previously quantified in mor humus profiles for dating purposes, although they have been quantified in surface samples of forest mor humus soils in a survey of their dispersal around industrial sources (Renberg & Wik, 1985b). The SCP analyses conducted in this study, therefore, represent an assessment of their utility for dating recent mor humus soil profiles.

The SCP profiles produced for the mor humus cores proved relatively successful (Figures 4.3-4.10 & Figures 4.13-4.15), their form closely approximating those found in

Scottish loch sediments (Wik *et al.*, 1986; Wik & Natkanski, 1990; Rose, 1991; Rose *et al.*, 1995). The three main dating features ascribed to SCP profiles by Rose *et al.* (1995), the start of the SCP record, the marked increase in particle concentrations and the peak in SCP abundance (Figure 4.12), are identifiable in practically all of the soil profiles.

The rapid increase in SCP concentration evident in all of the Tulach Hill and the other five Perthshire sites is estimated to have occurred during the 1940s because it marginally predates known *c.*1950 fire events in the *Tulach 1* (Figure 4.3) and *Tulach 13* (Figure 4.9) cores. This date falls within the range of dates suggested for this feature in Scotland (1940s-1960s) by Rose *et al.* (1995), and the readily recognisable nature of the feature makes it a useful isochrone.

The start of the SCP record is evident in some of the profiles analysed, but in the others the core base post-dates the mid-nineteenth century and thus the beginning of the SCP profile. The validity of relying upon this isochrone in these soil profiles could, however, be called into question because the SCP quantification method used in this study lacks precision at low particle concentrations (Section 3.4.4). The exact start of the SCP record may not, therefore, be accurately resolved and caution must be used in interpreting this feature in the profiles. Independent dating methods, possibly 'wiggle matching' of AMS $^{14}C$ dates (Pearson, 1986), are needed to determine whether the start of the SCP record in these profiles is synchronous with those produced by the more accurate SCP analyses of lake sediment cores (Rose *et al.*, 1995). Notwithstanding this, however, approximate dates of the start of the SCP curve extrapolated from the rapid increase in SCP concentration (Feature B) by simple linear regression suggest that it lies within the approximate mid-nineteenth century period.

The peak in SCP abundance dated to approximately 1976-1980 in UK and Irish lake sediment cores (Rose, 1991; Rose *et al.*, 1995) is identifiable in some of the mor humus soil core SCP profiles. However, this potential dating feature cannot perhaps be relied upon in these cores because of the low resolution of the soil records in the upper horizons. The relatively unconsolidated nature of the surface litter meant that they could only be sectioned coarsely, *i.e.* *c.*5 mm sections, and the poor resolution means that the possible isochrone is unreliable.

The relative success of the exploratory SCP analyses conducted at the Perthshire sites suggests that they could be used to provide recent isochrones for the relative dating of moorland soil profiles, the technique may not only be applicable to lacustrine sediments

(Renberg & Wik, 1984, 1985a, 1985b; Wik & Natkanski, 1990; Wik *et al.*, 1986; Rose, 1991; Rose *et al.*, 1995). Whether SCPs could be used to date other terrestrial sediments remains to be tested, however, the potential for wider application of the technique is obvious.

### 4.4.3 Fire histories

The initial fears concerning the potential of mor humus soils for reconstructing fire histories in moorland, expressed in Section 4.1, proved to be unfounded. Muirburns do not generally combust the soil surface layers and destroy the sediment record of previous fire activity because although small-scale heathland fires can reach temperatures of up to 840°C (Whittaker, 1961), only about 8% of the heat generated is conducted to the soil (Packham, 1971; DeBano *et al.*, 1976). Soil temperatures only rise above 100°C after all the moisture has been liberated after prolonged heating, a situation rarely achieved under small-scale muirburns (Cromer and Vines, 1966; Roberts, 1965). As a result controlled moorland fires are not represented in soil profiles by major layers of macrofossil charcoal, as may be the case in some peatland systems following catastrophic, uncontrolled fires (Maltby, *et al.*, 1990; Tolonen, 1985) but microscopic examination of sediment samples is necessary to detect the characteristic increased abundance of all sizes of microscopic charcoal.

The analyses conducted at Tulach Hill also demonstrate that the accumulation rates of mor humus soils, although relatively slow in comparison with peats and lake sediments, approximately 0.24-0.61 mm per year at Tulach Hill, are generally sufficient for individual fires to be resolved. Fire histories approaching 190 years in duration were produced from cores of up to 76 mm in length on Tulach Hill but given deeper soil sequences longer records of fire activity could be reconstructed.

One of the primary fears expressed before the analyses were conducted was that because of the large numbers of small fires set on moors on a regular basis sediment records of local fire activity would be obscured or 'masked' by charcoal from nearby or extra-local fires. This fear proved, however, to be unfounded. Charcoal assemblages produced by *in situ* fires were generally identifiable by distinct increases in particle abundance across the range of sizes quantified, and in contrast periods of nearby but *ex situ* fire activity were characterised by very low sediment charcoal contents. These results suggest that microscopic charcoal dispersal around muirburns is surprisingly restricted, *i.e.* most charcoal produced remains fairly close to the parent fire, and as a consequence histories of local fire activity are not obscured by 'background' charcoal from indeterminable source areas (Issues of charcoal dispersal around muirburns are discussed fully in Chapter 5).

Analysis of the charcoal assemblages produced by known *in situ* fires in the Tulach Hill cores illustrated that whilst some *in situ* fire events are readily discernible, because of the gross abundance of charcoal in the assemblages (*e.g.* 22 mm depth in *Tulach 1* and 9 mm depth in *Tulach 4*) others are rather less easily identified (*e.g.* 43-44 mm and 53-54 mm in *Tulach 2*) and require an appreciation of the distribution of charcoal across the range of size classes. Unequivocal identification of pre-aerial photograph fires by eye alone is, therefore, not always possible. For this reason linear discriminant analyses were used in an attempt to differentiate between *in situ* and *ex situ* fires in a more quantitative way using the quantities and size class distributions of charcoal in assemblages.

The linear discriminant function derived from all six of the size class variables was very effective at discriminating between charcoal assemblages produced by *in situ* and *ex situ* fires, 98.53% were correctly classified (Table 4.4). However, a discriminant analysis using total charcoal abundance alone as the discriminatory variable was also relatively effective at differentiating the assemblages from different origins, classifying 89.71% of the assemblages correctly (Table 4.5). These results suggest that both the total abundance of charcoal in an assemblage, *in situ* assemblages are generally characterised by high charcoal abundance, and the size class distribution of the charcoal particles are both important factors contributing to the effectiveness of the discrimination process.

What size class characteristics of the assemblages are most important in determining effective discrimination? The high degree of correlation between the size-class variables makes it difficult to assess the importance of individual variables in the derivation of the discriminant function. However, the relative performance of the different combinations of size class variables in the series of discriminant analyses conducted in Table 4.3 suggest that differences in the proportions of particles in the size classes E (250-500 μm) and C (63-125 μm) between *in situ* and *ex situ* assemblages are most influential in the discrimination process. Why this relationship exists is not immediately clear from this data. Conventional theory (*i.e.* Clark, 1988a) would suggest that particles in the largest size classes, those most resistant to dispersal from the fire site, might be expected to be most prevalent in and conspicuous components of *in situ* assemblages, and smaller particles to be present in greater proportions in *ex situ* assemblages. Particles in the less extreme medium size ranges might be expected to be more ubiquitous in all assemblages. In the discriminant analyses performed on the Tulach Hill data set, therefore, one might have expected the largest and smallest size class variables (F and A respectively) to exert greater influence on the performance of the discriminant analyses than the medium size classes. That this is not the case suggests that rather more complex charcoal production, dispersal and sedimentation processes than previously acknowledged may be occurring, such processes are discussed further in Chapter 5.

Partial ignorance of the taphonomic processes which determine the size class distributions of the different charcoal assemblages, however, does not detract from the efficacy of the linear discriminant function derived at differentiating *in situ* assemblages from *ex situ* ones, or the validity of using the discriminant function for classifying unknown assemblages. Table 4.6 displays the results gained by using the Tulach Hill discriminant function to classify unknown assemblages, *i.e.* those assemblages not known to be of either *in situ* or *ex situ* origin. The nine charcoal assemblages classified as the probable product of *in situ* fires by the discriminant function were all classified with consistently high posterior probabilities of classification (>81.33% in all cases) suggesting that classification was relatively reliable (Klovan & Billings, 1967; Gauch, 1982). With this data set, however, there is no unequivocal means of checking whether the discriminant function is correctly allocating the charcoal assemblages. A set of known *in situ* and *ex situ* charcoal assemblages, not used in the calculation of the discriminatory function, are needed to validate the effectiveness of the discriminant function at classifying unknown assemblages further.

The Tulach Hill discriminant function was not used to verify the identification of *in situ* versus *ex situ* charcoal assemblages from the five additional Perthshire moor cores. A discriminant function derived from a much larger data set and containing charcoal assemblages from a wide number of moors is needed before the technique could be used more widely. The use of the discriminant analysis approach at Tulach Hill does, however, suggest that it may be a useful technique if developed more fully. The interpretations of fire activity from the Auldallan Hill, Blacklaw Hill, Gallow Hill, Trochry Hill and Happas Farm cores are therefore rather more subjective, and perhaps less accurate, than those produced for the Tulach Hill cores. The cores do, however, indicate that charcoal analyses of mor humus soils can be used to reconstruct fire histories at a range of sites and have microscopic charcoal profiles of broadly comparable form and character.

The charcoal analysis and charcoal assemblage characterisation methods used in this study are at an early stage in their development. Much larger data sets are needed to develop them to their full potential and to verify their validity and applicability, however, the available results do suggest that the techniques have appreciable potential. Used together aerial photograph and palaeoecological charcoal analyses represent a potentially powerful tool for reconstructing moorland burning regimes. The long-term perspective provided could be used to elucidate the role of fire in a great number of contentious debates facing ecology in moorland contexts, *e.g.* the role of fire in heathland initiation, the long-term decline of *Callunetum*, and the succession of heather by scrub-woodland to name but a few.

# Chapter 5: Charcoal Taphonomy


### Abstract

The taphonomy of microscopic charcoal around small moorland vegetation fires is studied using aerial photographs and palaeoecological charcoal analyses of short soil cores. The quantities of charcoal produced by individual fires is found to be highly variable and charcoal particles of varying sizes are found to be produced in significantly different proportions. Smaller charcoal particles being produced in increasingly greater quantities than successively larger ones. The majority of charcoal particles produced by muirburns appear to be deposited within *c.*70-80 m of the parent fire, and the wind direction at the time of the fire appears to exert a strong control on charcoal particle dispersal. The predominant direction of charcoal particle dispersal is down-wind, relatively few are dispersed laterally or into the wind.


## 5.1 Introduction

The taphonomy of microscopic charcoal has received relatively little attention in comparison with pollen taphonomy and as a consequence is relatively poorly understood. The poor level of understanding of charcoal dispersal and deposition processes is widely acknowledged as the greatest factor restricting the efficacy of charcoal analyses (*e.g.* Battson & Cawker, 1983; Anderson & Davis, 1986; Patterson *et al.*, 1987). The use of microscopic charcoal analyses in palaeoecological and palaeoenvironmental studies has increased markedly in recent years and it is critical that understanding of microscopic charcoal taphonomy is improved to ensure that future interpretations of charcoal data are realistic and founded upon fact rather than supposition.

The taphonomy of microscopic charcoal produced by muirburns has not been studied directly before. The experiments of Evans & Allen (1971), to assess nutrient losses in heather smoke, and the theoretical treatment of charcoal dispersal in Danish moorlands by Odgaard (1993) represent the most relevant work to date. Managed by regular burning moorlands are potentially complex systems in which to study microscopic charcoal taphonomy because large quantities of charcoal are produced annually by a number of discrete, small-scale fire events scattered over the moor. However, they also provide much scope for experimentation because the fires are small, relatively uniform in character, have well defined boundaries, and large numbers of them are conducted on a regular basis.

My original intention was to perform a number of controlled muirburns and to measure dispersal around them directly, both during and for an extended period after the fires. However, the logistics of securing sufficient experienced manpower to control the burns within the restrictive temporal constraints imposed by appropriate weather conditions proved impossible. The alternative approach adopted, using aerial photographs and fossil microscopic charcoal assemblages from soil cores, does not provide such direct evidence of dispersal processes, but it does provide a valuable insight into production processes, the spatial patterns of dispersal around muirburns and the relative importance of different taphonomic processes.

## 5.2 Outline of methodology

The charcoal dispersal study was conducted on Tulach Hill, Blair Atholl, Perthshire. Maps of muirburns (*c.*1940/50-1988) were produced from aerial photographs using PC ARC/INFO (Figures 4.1 & 4.2). These were used to define the network of 16 mor humus soil cores shown on Figure 3.1. Cores *Tulach 1, 4, 12 & 13* were taken from locations burned once during the post-*c.*1950 period, cores *Tulach 11 & 16* from areas burned twice, and the others from positions known not to have been burned during the post-1940/50 period.

The distances between each of the cores and the three nearest burns on each of the eight aerial photograph maps of muirburns were measured using the GIS. The aim of this exercise was to determine the possible sources of charcoal in the cores. It was assumed that the muirburn closest to the core were most likely to have contributed most of the input of charcoal. As it was impossible to determine the source of the charcoal in core assemblages which had been in close proximity to more than one burn for a given time period, any core within <250m of more than one burn was excluded from the analysis. The 250m limit was decided upon as a conservative estimate of the likely distance over which significant quantities of charcoal particulates were likely to be dispersed around such small, low intensity fires. (The subsequent analyses of dispersal proved this estimate to be satisfactory as relatively few charcoal particulates were found to be dispersed over distances in excess of 70-80m; see Section 5.3.2).

The approximate chronology of the upper sediments in the cores interpolated between the surface and the *c.*1940 SCP isochrone by linear regression was used to identify charcoal assemblages contemporaneous with each of the AP coverages of muirburn. Although this method of chronology determination has a limited degree of accuracy it worked satisfactorily well for the purpose of this study. As illustrated in Figures 4.3-4.10 charcoal assemblages produced by individual fire events were manifested in the soil cores by obvious, discrete peaks in charcoal abundance whilst periods of non-local fires were characterised by an almost absence of charcoal. This allowed assemblages of charcoal produced by individual fire events to be readily recognisable within the approximate chronologies produced. In addition, where possible charcoal assemblages in close proximity to the SCP isochrone were used to maximise the degree of temporal accuracy and ensure the correct identification of assemblages.

Sixty-eight charcoal assemblages, seven known to have been produced *in situ* by fires and sixty-one produced and deposited at known distances from fires, were identified and used in the analyses of charcoal taphonomy. These sixty-eight assemblages represent a small proportion of the *c.*750 charcoal samples counted, the remainder were not utilised in the analyses because their source could not be reliably determined. Only those charcoal assemblages which were believed to have been accurately identified and whose source fires were determined beyond reasonable doubt were used in the analyses.

## 5.3 Results

### 5.3.1 Charcoal production

The amount of charcoal produced by individual burns was found to be highly variable. A fact well illustrated by the charcoal assemblages recovered from '*in situ*' fires on Tulach Hill (Figure 5.1). These assemblages are composed of particles produced, deposited and incorporated into the soil within the boundary of known fires.

Table 5.1: Quantities of charcoal produced by, and deposited within the mor humus beneath, seven Tulach Hill muirburns.

| Assemblage | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Particle concentration (no./g/yr$^{-1}$) | 2070 | 1400 | 320 | 465 | 550 | 540 | 455 |

There are marked differences in the quantities of charcoal produced and incorporated in the sediments within the individual burns, with values ranging from only *c.*320 particles/g/yr$^{-1}$ to 2070 particles/g/yr$^{-1}$. The causes of these differences are not immediately clear as charcoal production is potentially controlled by a complex range of variables: fuel volume and moisture content; fire size, temperature, duration and intensity; prevailing weather conditions at the time of the fire event; *etc.* Such factors interact in an inextricable manner to control charcoal production and their individual influence cannot be determined from the sedimentary charcoal record, *i.e.* fire characteristics cannot be reconstructed and thus little can be assumed about the nature of the parent fire. Sedimentary microscopic charcoal assemblages, therefore, merely indicate that biomass has been burned (Edwards, 1987). Scott & Jones (1991) have used measures of charcoal particle reflectance to determine approximate fire temperatures but alone such information is of limited use to the charcoal analysts and palynologist.

The fact that highly variable quantities of charcoal can be produced by fires suggests that great care is needed when interpreting the magnitude of charcoal peaks in sedimentary charcoal records (Swain, 1973). The very largest charcoal peaks may represent local burning, but smaller ones may also and should not be dismissed as the product of less local or even regional fire activity.

The size class distributions of the *in situ* assemblages were studied to determine whether a relationship exists between the quantity of particles produced by fires and the proportions of particles in each size class. Are equal quantities of each size produced by individual fires or do differentials in production exist?

Figure 5.1: The percentage size class distributions of charcoal particles in the seven *in situ* charcoal assemblages from Tulach Hill.

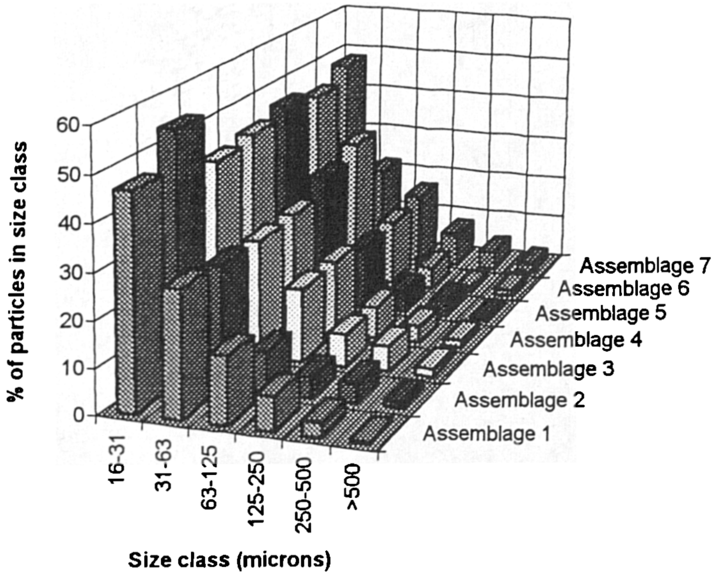



Figure 5.1 illustrates that the proportions of particles produced across the range of size classes are very similar for the seven assemblages sampled, despite the large differences in the total numbers of particles produced (Table 5.1). As size class increases the proportion of particles within that size class falls approximately logarithmically. Approximately 46.8% of the charcoal particles produced fall into the 16-31 μm size class, 27.5% into the 31-63 μm class, 14.5% into the 63-125 μm class, 6.2% into the 250-500 μm class and only 1.3% into the >500 μm class. The slight discrepancies between assemblages are highlighted in Table 5.2.

Table 5.2: The proportions of charcoal particles in each of the size classes for the seven *in situ* charcoal assemblages.

| | Size class (μm) | | | | | |
|---|---|---|---|---|---|---|
| | **16-31** | **31-63** | **63-125** | **125-250** | **250-500** | **>500** |
| **Assemblage 1** | 46.5% | 27.7% | 14.8% | 7.4% | 3.2% | 0.4% |
| **Assemblage 2** | 54.5% | 26.5% | 8.8% | 4.5% | 4.4% | 1.3% |
| **Assemblage 3** | 43.0% | 26.1% | 16.4% | 7.3% | 5.5% | 1.8% |
| **Assemblage 4** | 44.4% | 26.6% | 16.6% | 7.1% | 3.7% | 1.7% |
| **Assemblage 5** | 46.4% | 30.2% | 14.1% | 4.8% | 3.6% | 0.8% |
| **Assemblage 6** | 44.4% | 33.5% | 14.7% | 4.9% | 1.1% | 1.3% |
| **Assemblage 7** | 48.2% | 21.8% | 16.3% | 7.5% | 4.1% | 2.1% |
| ***Mean*** | *46.8%* | *27.5%* | *14.5%* | *6.2%* | *3.7%* | *1.3%* |

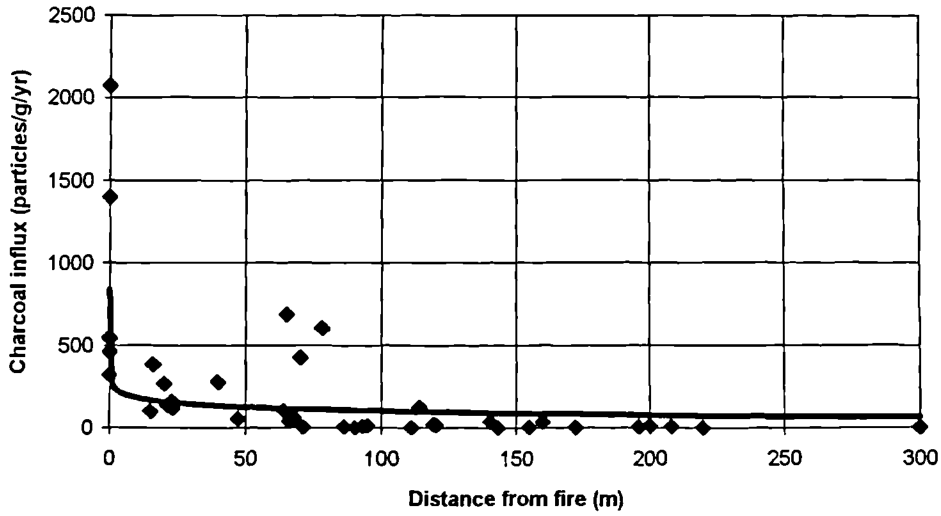
The data set of only seven charcoal assemblages is rather small to be making unequivocal assertions about production processes. However, the close agreement of the size class distributions within the sample suggests that a bias in the production of different sized charcoal particles (here-after, 'production-bias') would appear to exist, smaller particles being produced in greater abundance than progressively larger ones. (The implications of production-bias are important for the interpretation of sedimentary charcoal profiles, these are discussed further in Section 5.4.1.)

### 5.3.2 Distance of dispersal

There is much debate about the distances over which microscopic charcoal particles of different dimensions can be transported (*e.g.* Patterson *et al.*, 1987; Clark, 1988a; Clark & Royall, 1995). Despite attempts to quantify charcoal fluxes from fires experimentally (*e.g.* Evans & Allen, 1971; Clark, 1983; Wein *et al.*, 1987), and several theoretical models of dispersal processes the issue has been far from resolved. Charcoal taphonomy in moorlands in particular has received little attention and the distances over which charcoal particles can be transported before deposition and sedimentation are unknown.

Figure 5.2 illustrates the relationship between total charcoal particle influx and the distance from the fire for 41 charcoal assemblages recovered from Tulach Hill. The seven values plotted on the y-axis represent *in situ* assemblages, with dispersal distances of 0 m, the others fall along a distance gradient of between 15-300 m from fires. It is important to note that the charcoal assemblages presented are the product of many different fire events and that the areal pattern of charcoal dispersal is, therefore, complicated by differential charcoal production, wind speeds at the time of the fires and climatic conditions following the fire events. Consequently the relationship between charcoal abundance and distance from the fire is not a simple one, however, a reasonably coherent pattern is displayed.

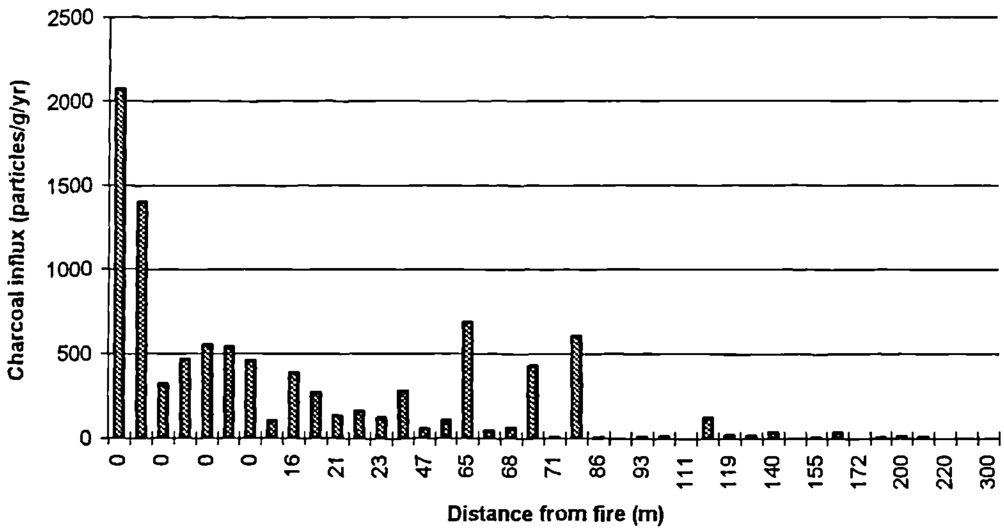
Figure 5.2: Microscopic charcoal dispersal from muirburns on Tulach Hill.




A logarithmic trendline has been fitted to the charcoal dispersal data in Figure 5.2. Charcoal deposition away from the Tulach Hill fires approximates a leptokurtic curve, *i.e.* particle abundance decreases very rapidly away from the source and then remains low but relatively steady over greater distances. Such a pattern has been observed during studies of the dispersal characteristics of a wide variety of other microscopic particulates (Colwell, 1951; Green & Lane, 1964; Turner, 1964; Janssen, 1966, 1984; Raynor *et al.*, 1972; Prentice, 1985; Okubu & Levin, 1989).

Figure 5.3 illustrates the relationship between dispersal distance and charcoal influx for each individual charcoal sample. (Care should be taken in interpreting the x-axis. It is not a continuous distance scale, the distances from each fire are displayed as discrete values, *i.e.* the seven left-most assemblages are all *in situ* ones with distances from source of 0 m. Only every other distance measure is displayed because of the axis scaling). Charcoal influx generally declines with increasing distance from the parent fire in a fairly constant manner up until 65 m from the fire, between 65 and 78 m there are three anomalously high charcoal abundance values. Beyond *c.*80 m generally minimal amounts of charcoal were deposited.

Figure 5.3: The magnitude of charcoal dispersal with distance from Tulach Hill muirburns.




The three very high influx values at 65, 70 and 78 m respectively are of particular interest. Why are such large quantities dispersed uncharacteristically long distances? Examination of these three assemblages and the morphology of their parent burns provides a possible explanation for the phenomena, and also an insight into the mechanisms of dispersal (See Figures 5.4a, b & c). Each of the three anomalous assemblages were deposited at the end of long thin burns.

Four samples were collected around the margin of the fire in Figure 5.4a and although the location 65 m from the fire boundary is considerably further from the fire than the other three, which are located approximately perpendicular to the long axis of the burn, it received a far greater influx of charcoal. Likewise in Figure 5.4b the position 78 m from the end of the long-axis of the burn received a far greater quantity of charcoal than the closer lateral one. In the third instance, Figure 5.4c, charcoal influx 70 m from the end of the burn is only marginally lower than within the burn itself.

It is proposed that the phenomena can be explained by the direction of the wind at the time of the fire. Unconfined vegetation fires spread rapidly in the direction of local wind or upslope in uneven terrain and in uniform fuel on smooth terrain fires grow from the point of ignition to form an elongated shape, a shape which is the same in savannah, shrub or timber crown fires (Crutzen & Goldammer, 1992). On moorland and heath the

Figure 5.4a: The dispersal of microscopic charcoal around an individual muirburn on Tulach Hill. The hatched area represents a plan view of the muirburn and locations A, B, C & D the positions of four soil cores around the burn. The graphs provide information on the quantity and size class distribution of charcoal particles deposited at each location by the fire.

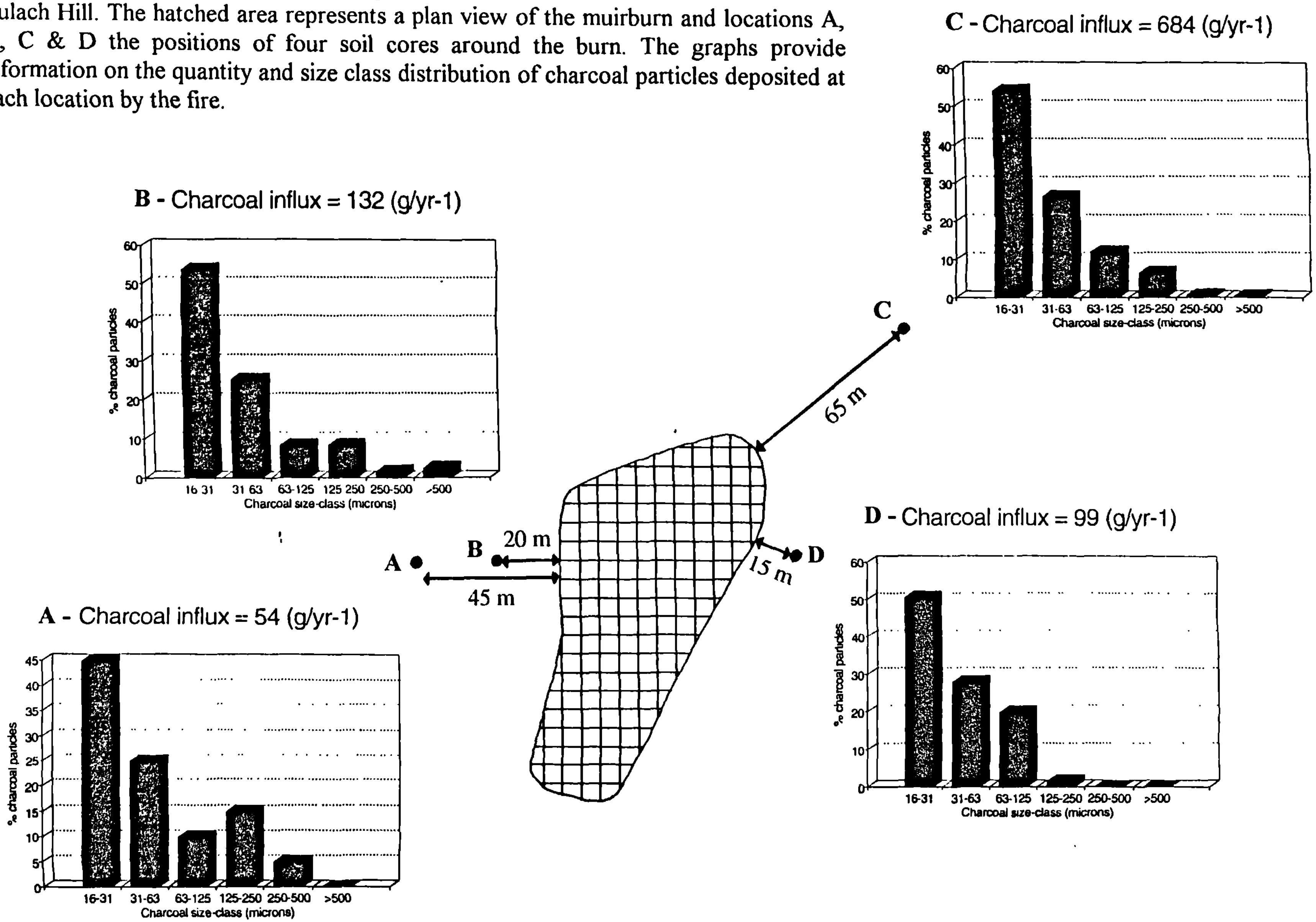


Figure 5.4b: The dispersal of microscopic charcoal around an individual muirburn on Tulach Hill. The hatched area represents a plan view of the muirburn and locations A & B the positions of two soil cores around the burn. The graphs provide information on the quantity and size class distribution of charcoal particles deposited at each location by the fire.

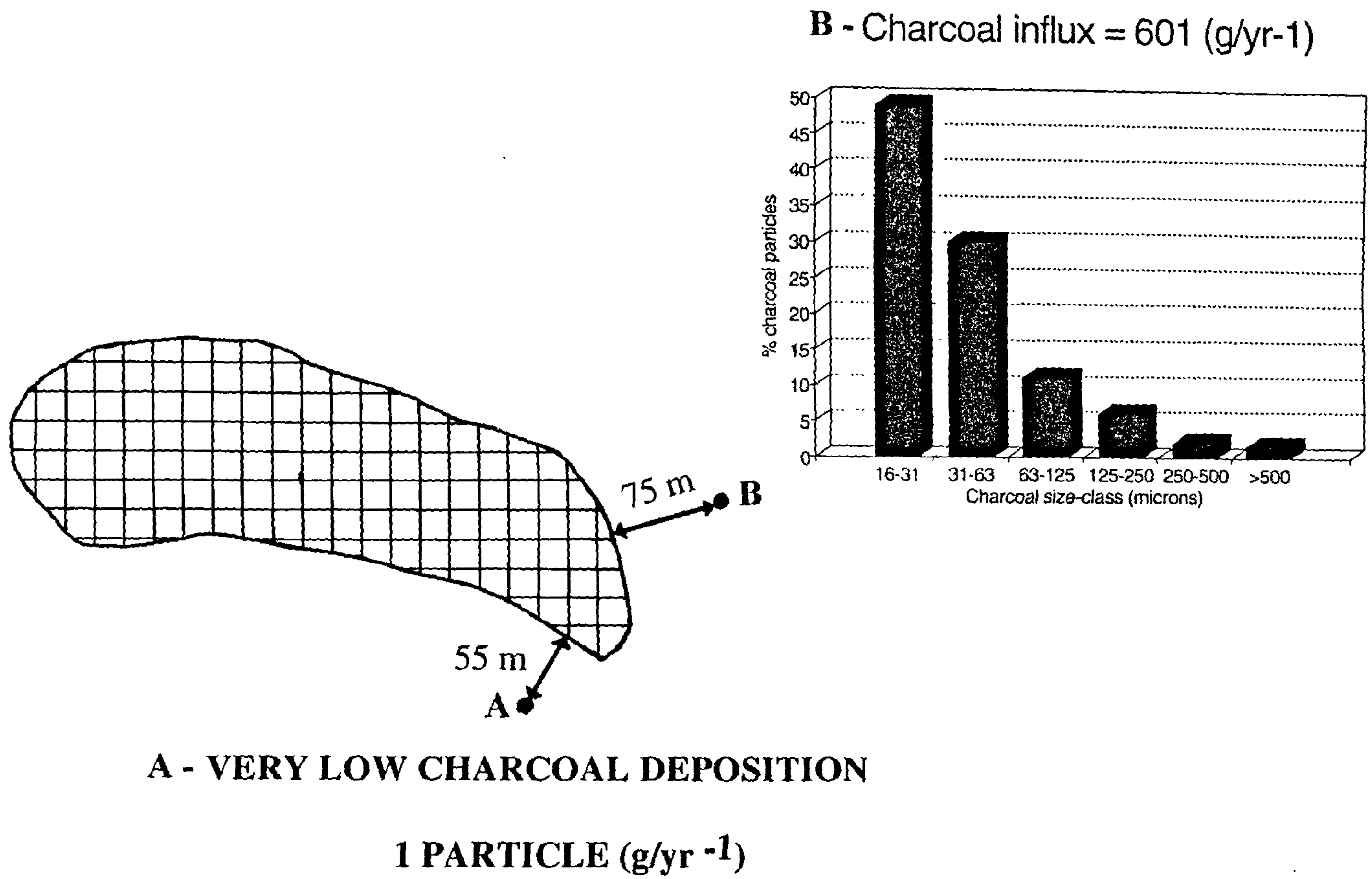
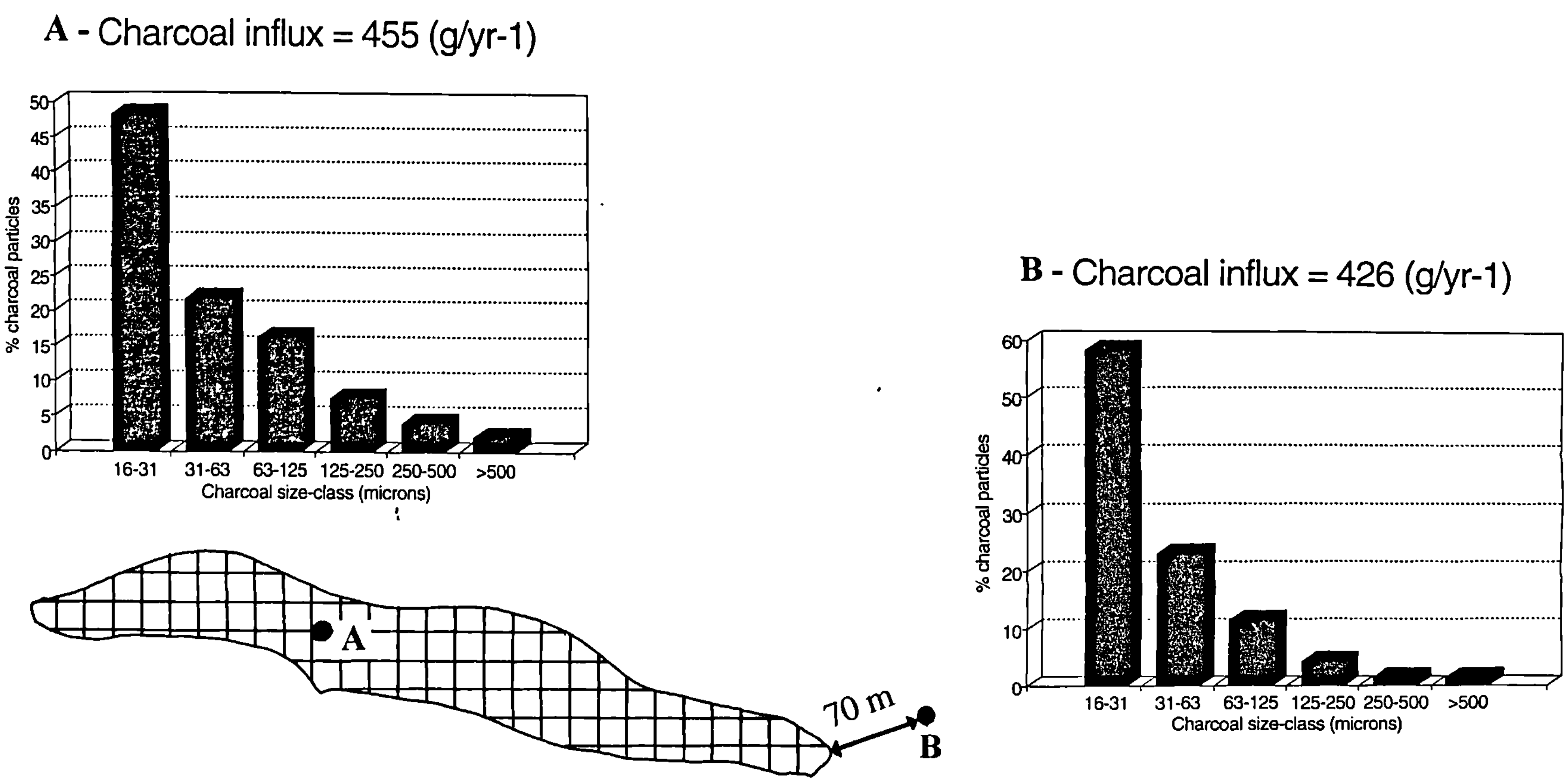


Figure 5.4c: The dispersal of microscopic charcoal around an individual muirburn on Tulach Hill. The hatched area represents a plan view of the muirburn and locations A & B the positions of two soil cores. The graphs provide information on the quantity and size class distribution of charcoal particles deposited at each location by the fire.



vast majority of muirburns are allowed to run with the wind to form long thin burns of any length and ideally not wider than 30 m across (Muirburn Working Party, 1977; Phillips *et al.*, 1993). Although the flanks of muirburns are controlled by beaters, on areas of relatively flat moor their long-axes are likely to be aligned with the direction of the wind at the time of burning.

All three of the Tulach Hill burns (Figure 5.4) were conducted on flat areas of the moor and all have obvious long-axes. It is proposed that the anomalous assemblages received inordinately large influxes of charcoal because they were down-wind of the fires. Smoke and particulates are dispersed down-wind of fire (Chamberlain, 1975; Clark, 1983). The lack of charcoal dispersed perpendicular to the long-axes of the burns, Figure 5.4a & b, suggests that lateral dispersal is limited. Some particles are deposited laterally, the consequence of random turbulent eddies (Gregory, 1945) or temporary changes in wind direction, however, the principal direction of particulate dispersal is in a down wind direction. The dependence of charcoal dispersal on wind direction has important implications for the interpretation of charcoal assemblages in the moorland system, and perhaps other environments, these implications are discussed in Section 5.5.3.

### 5.3.3 Differential dispersal of different sized charcoal particles

It is generally accepted, mainly on the basis of theoretical models founded upon pollen and sand dispersal, that small charcoal particles are transported further from source fires than larger ones (Patterson *et al.*, 1987; Clark, 1988a). Few studies of charcoal taphonomy have, however, been able to provide convincing data to illustrate that this is actually the case (*e.g.* Clark, 1983; Wein *et al.*, 1987).

Figure 5.5a: The dispersal of charcoal particles in the 16-31 μm, 31-63 μm and 63-125 μm size classes from muirburns on Tulach Hill.

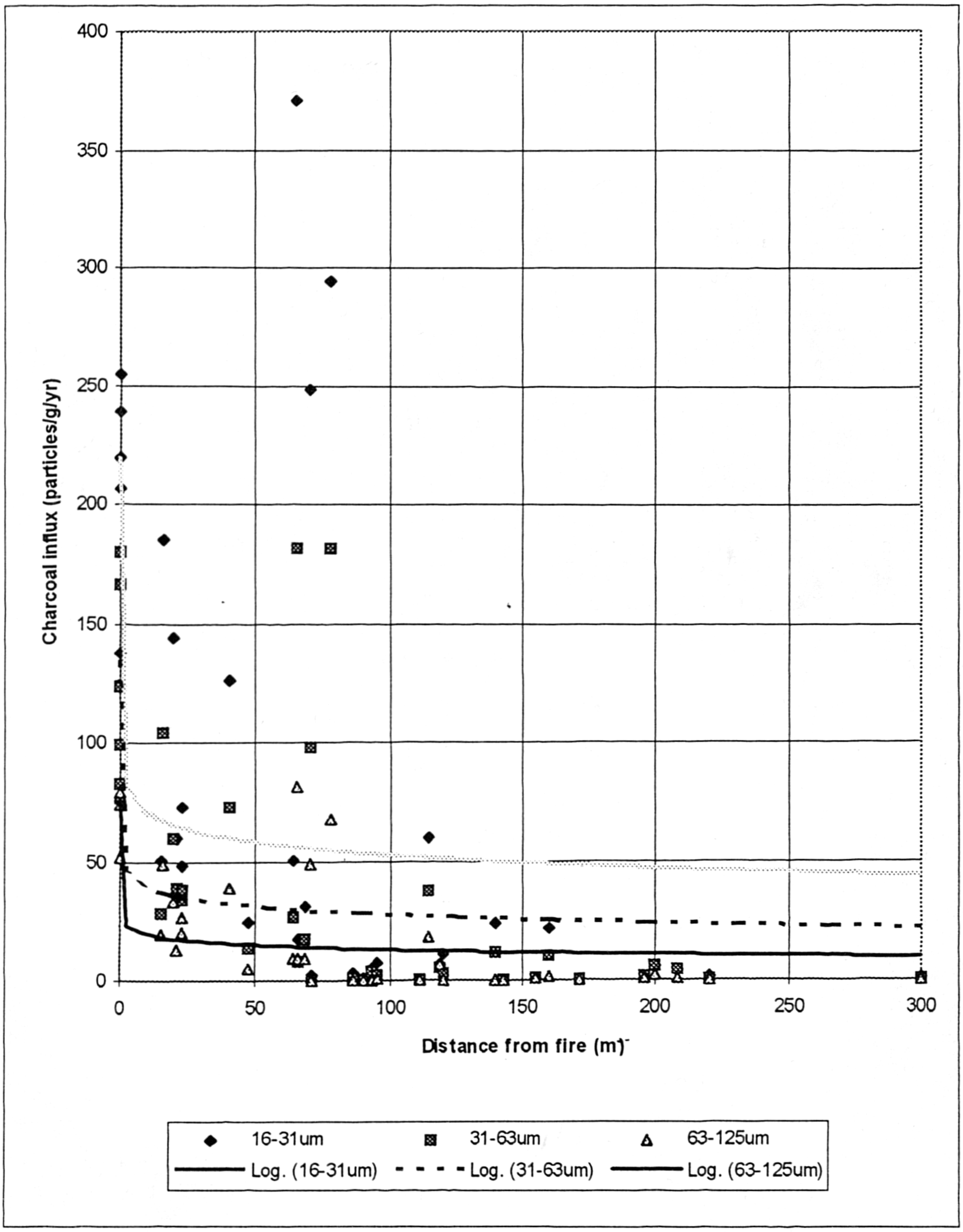
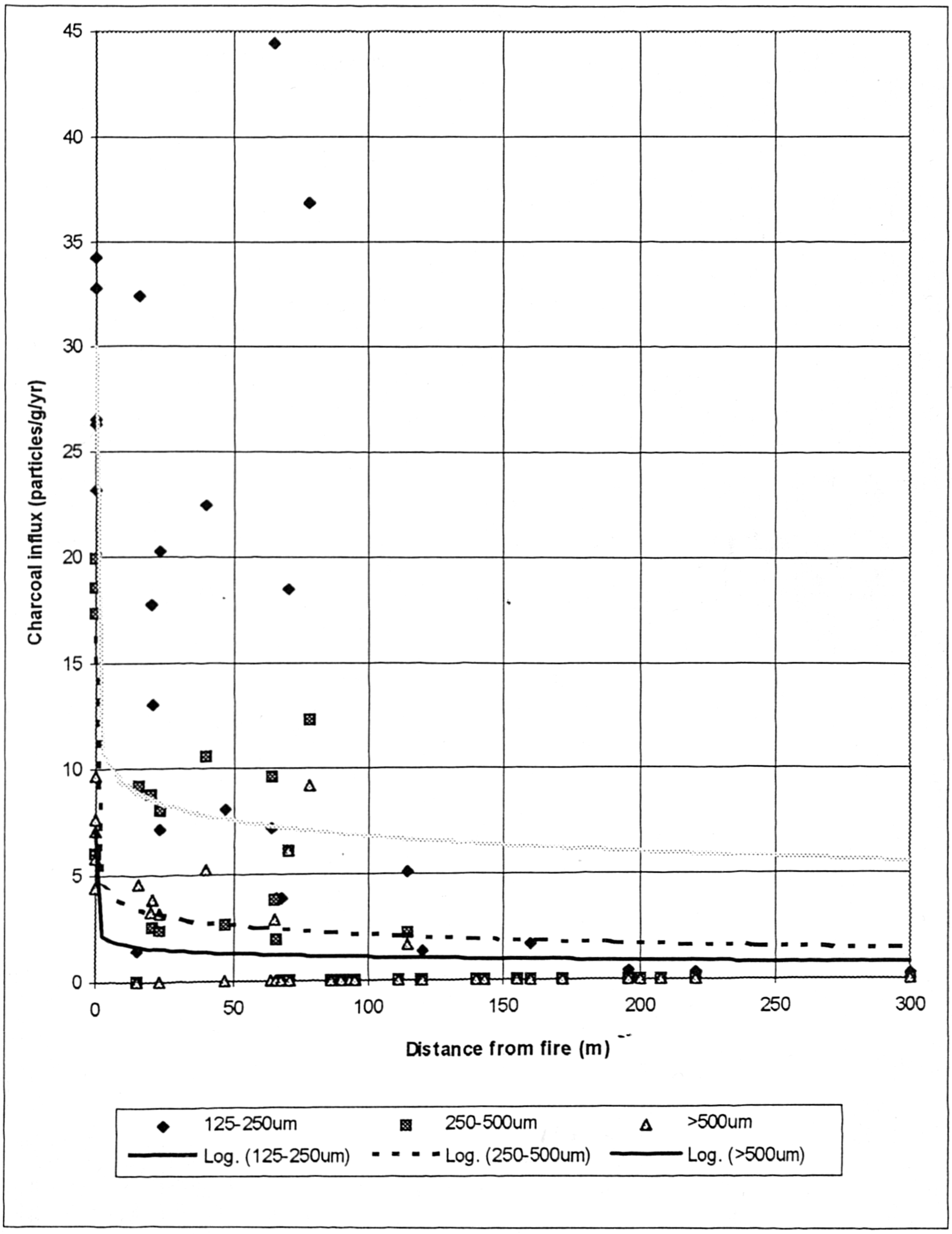


Figure 5.5a: The dispersal of charcoal particles in the 125-250 μm, 250-500 μm and >500 μm size classes from muirburns on Tulach Hill.



Figures 5.5a & b illustrate the relationship between the range of particle sizes quantified at Tulach Hill and the distances over which they were dispersed from fire events. Logarithmic trendlines have been plotted for each of the six size classes. The dispersal curves for all of the size classes are leptokurtic, the quantity of charcoal deposited declining rapidly away from the source before levelling out. The dispersal curves are 'stepped' according to size class, a feature attributed to production and dispersal biases. Smaller particles are produced in greater quantities than progressively larger ones, hence the relative magnitudes of the decay curves, and smaller, lighter particles have greater properties for dispersal than larger ones, a feature illustrated by the continued separation of the curves over the whole distance sampled.

There is a strong relationship between the sizes of particles and the distances over which they are dispersed, a relationship further illustrated by Figures 5.6a-5.6f.

Figure 5.6a: Dispersal of charcoal particles in the 16-31 μm size class.

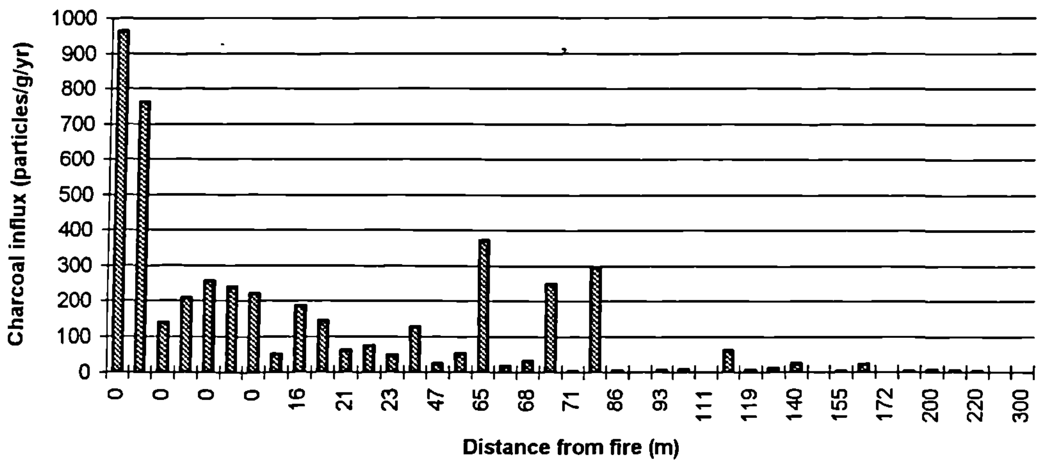
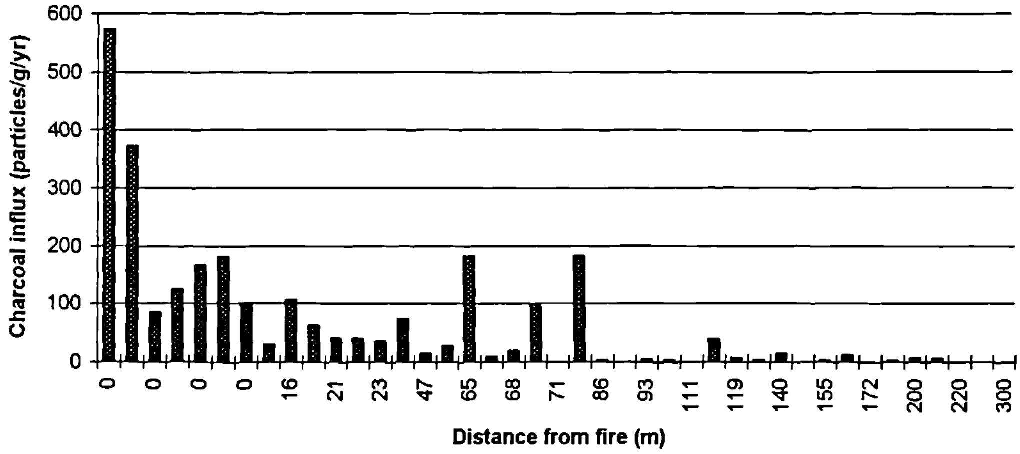
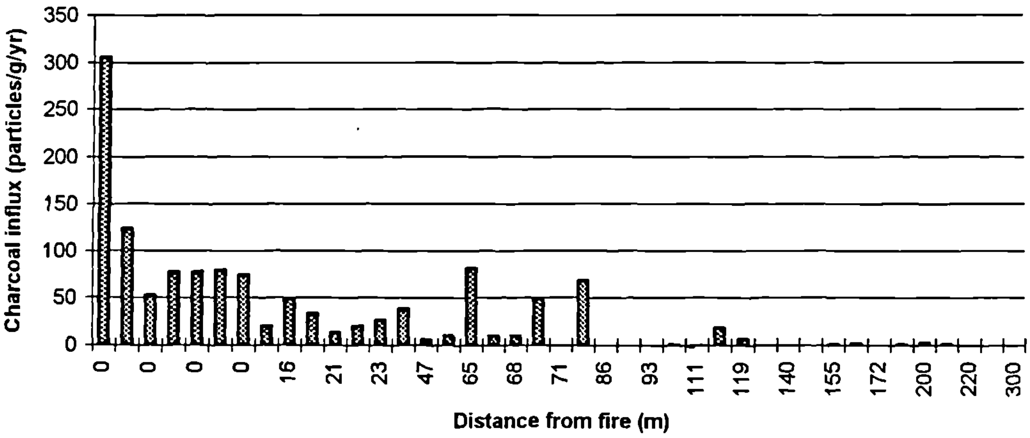


Figure 5.6b: Dispersal of charcoal particles in the 31-63 μm size class.



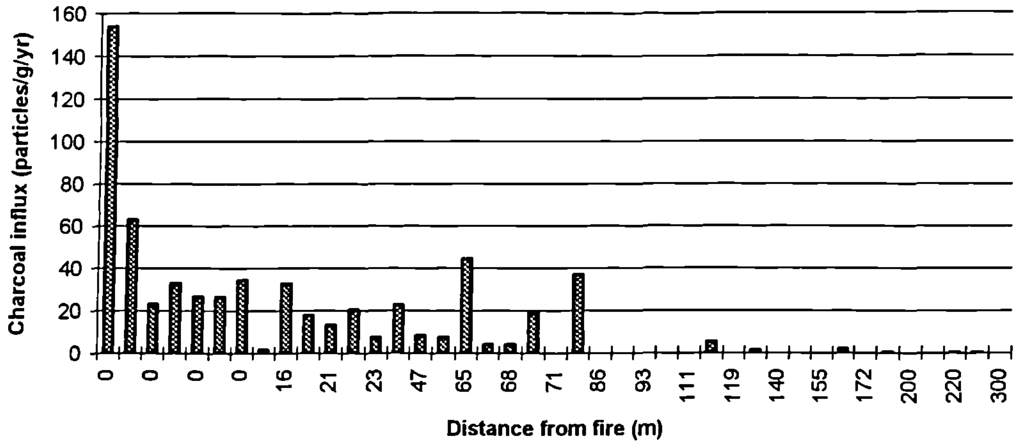

Notable quantities of the smallest particles (16-31 μm) are found in all but six of the assemblages sampled, those lacking small particles are all in excess of 85 metres from the source fires. Particles in the 31-63 μm size range are present in all but eight of the assemblages and in a number of instances notable quantities are dispersed up to 220 m from fires.

Figure 5.6c: Dispersal of charcoal particles in the 63-125 μm size class.



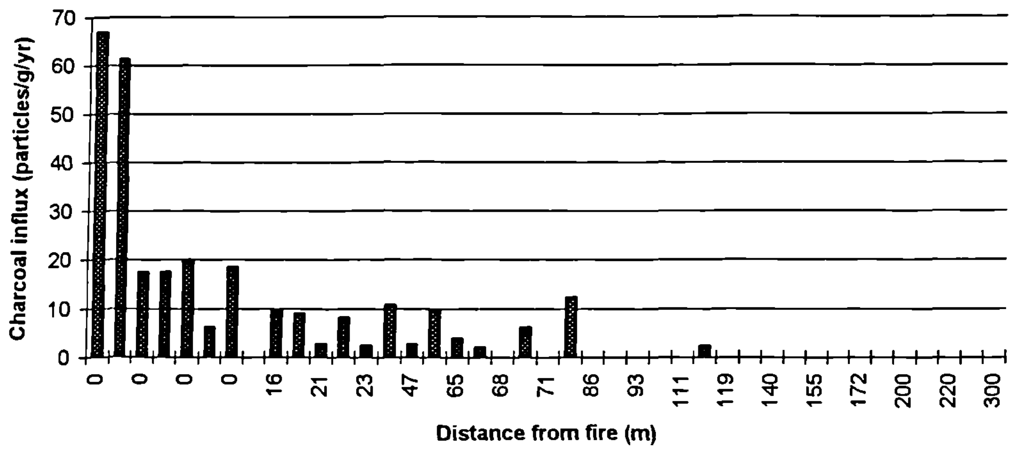

Particles in the 63-125 μm and 125-250 μm size ranges are absent from twelve and fourteen samples respectively but small quantities of both size ranges can be dispersed up to 300 m from fires.

Figure 5.6d: Dispersal of charcoal particles in the 125-250 μm size class.



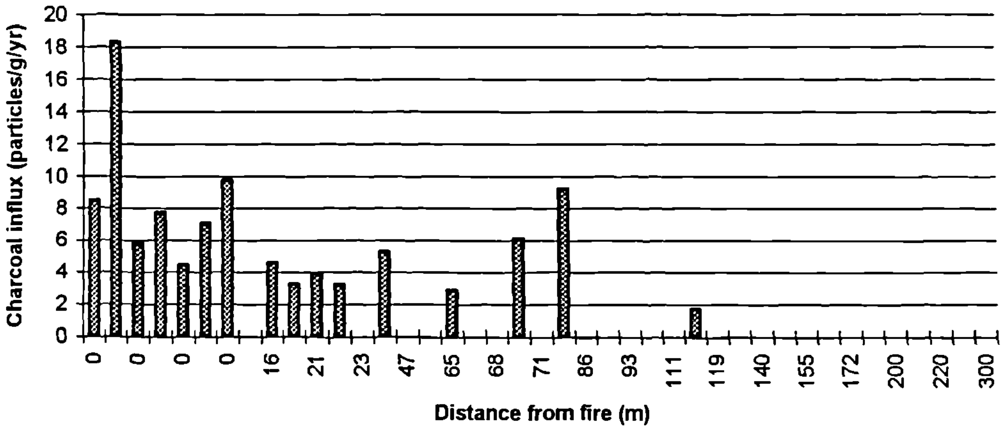

Particles in the 250-500 μm size class are not generally dispersed further than eighty metres and are absent from twenty-one of the forty-one samples.

Figure 5.6e: Dispersal of charcoal particles in the 250-500 μm size class.




Significant quantities of particles in the largest class, >500 μm, are present in only sixteen of the forty-one samples, and very few are deposited further than 80 m from the parent fires.

Figure 5.6f: Dispersal of charcoal particles in the >500 μm size class.

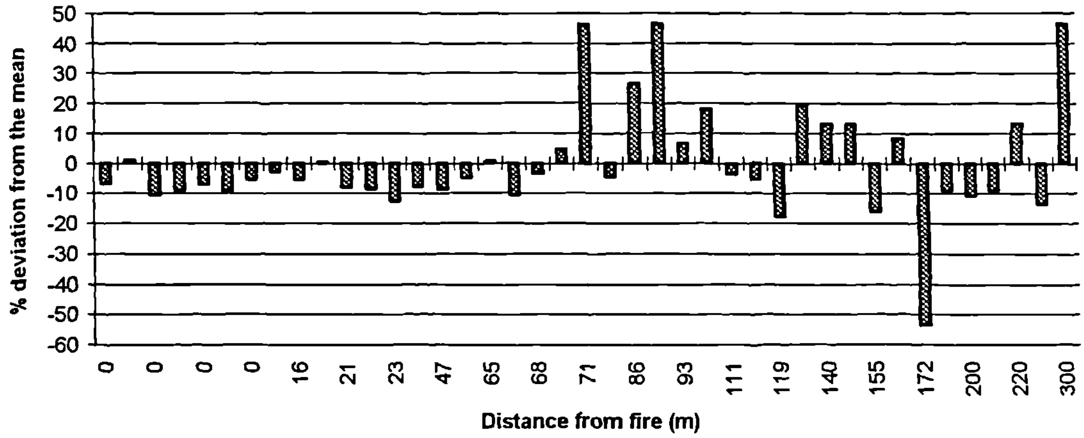



The range of distances sampled, up to 300 m, is insufficient to delimit the maximum distances over which charcoal particles of all sizes may be dispersed. However, the analyses indicate that particles in the two largest size classes are rarely dispersed further than 80-120 m. The smaller particles are often readily carried at least 300 m, evidently much greater networks of samples are necessary to determine maximal dispersal distances of the smaller particles.

In Chapter 4 a discriminant function was used to classify charcoal assemblages produced by *in situ* and *ex situ* fire events on the basis of their size class distributions, however, the differences between the assemblages was not fully explored. Figures 5.7a, b, c, d, e & f illustrate the differences between *in situ* and *ex situ* assemblages deposited over a range of distances from fires.

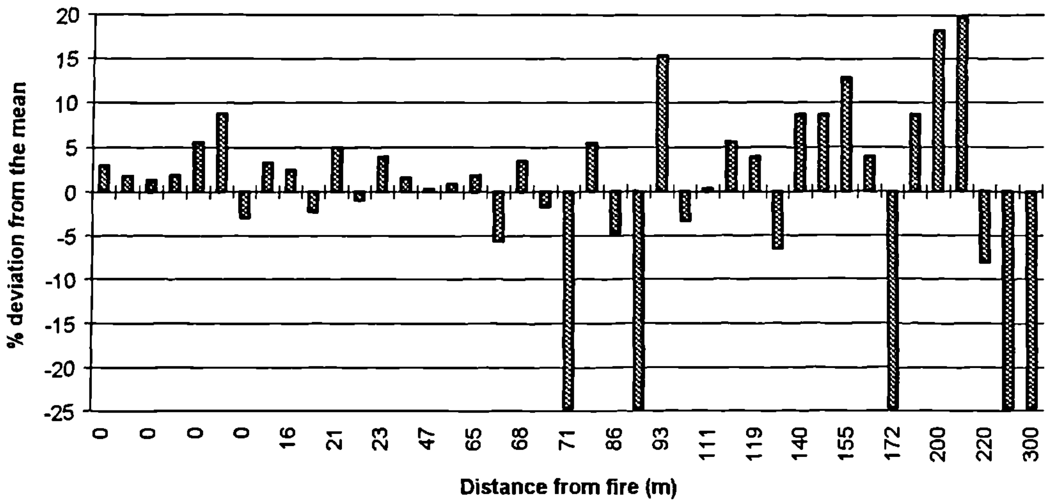
Figure 5.7: Percentage deviations from the mean distributions of particles in each of the six size classes:

a) 16-31 μm particles

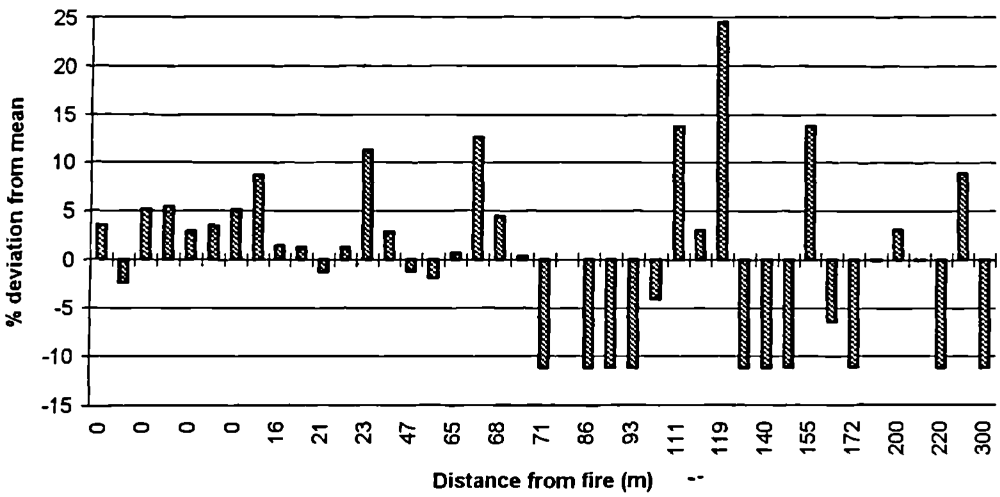



In general the *in situ* assemblages on the left of the diagram have approximately 5-10% less than average proportions of 16-31 μm particles, as do assemblages deposited up to *c.*70 m from fires. Beyond 70 m there is no obvious relationship between distance from the fire and the abundance of 16-31 μm particles, approximately half of the assemblages have above average (between *c.*5-45%) quantities of small particles whilst the other half have below average abundance. The *in situ* assemblages and those up to 70 m away from fires generally have above average proportions of particles in the 31-63 μm and 63-125 μm size ranges (Figures 5.6b & 5.6c). Over distances in excess of *c.*70 m charcoal abundance in the assemblages vary greatly between well in excess and well below the mean figure.

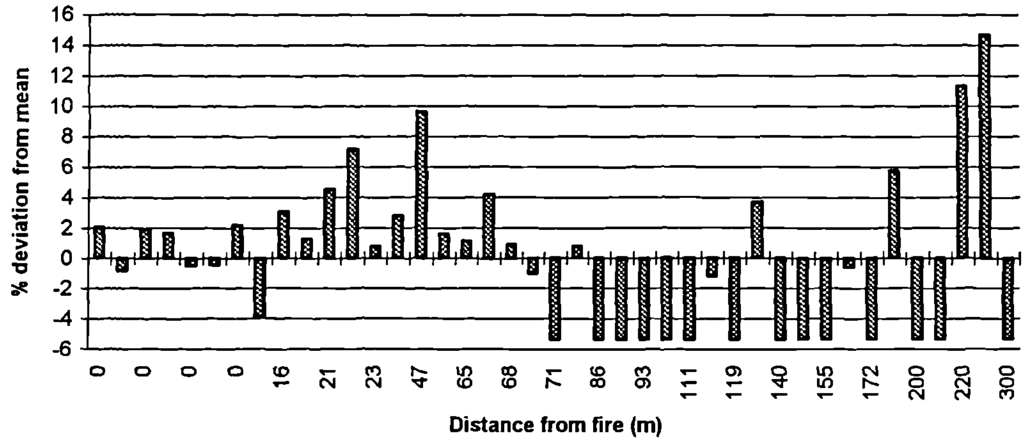
b) 31-63 μm particles



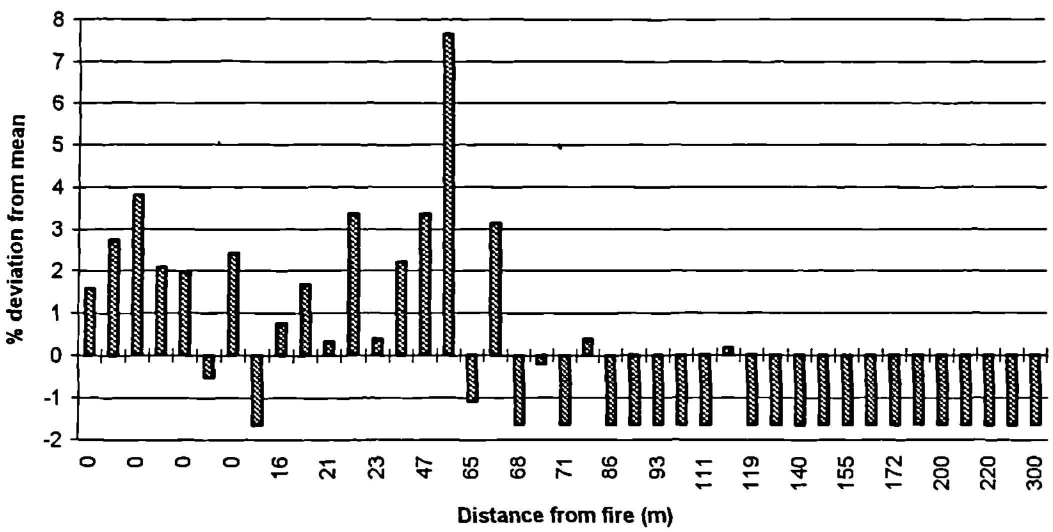

c) 63-125 μm particles



d) 125-250 μm particles

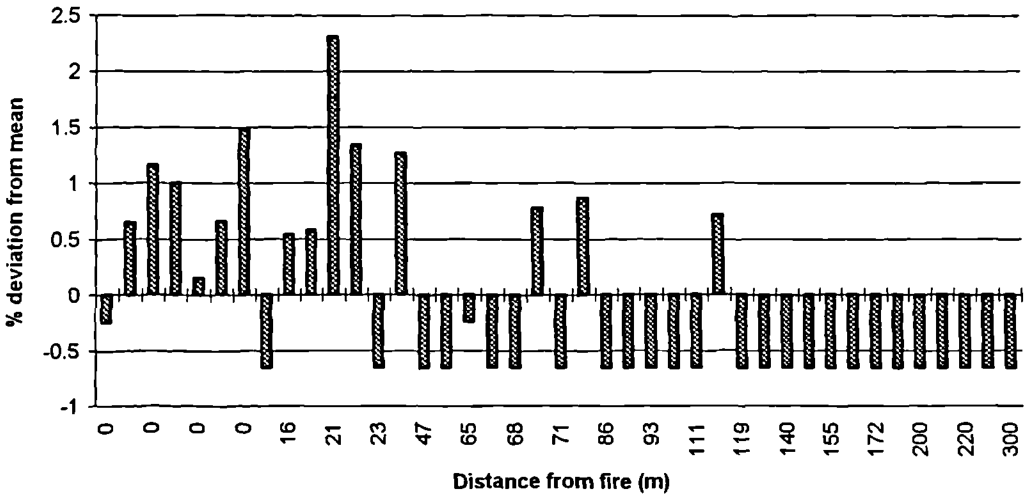



e) 250-500 μm particles




The *in situ* and <70 m assemblages contain generally higher than average proportions of 125-250 μm and 250-500 μm particles, whilst more distant assemblages are relatively deficient of particles in these size classes.

f) >500 µm particles




Particles >500 µm are present in above average proportions in the *in situ* assemblages and those <40 m from fires. Assemblages at >40 m from fires are generally deficient in particles of such large dimensions.

A number of relationships in the data set are worthy of reiteration. The *in situ* assemblages generally contain greater than average proportions of particles in all size classes apart from the smallest, which they contain in lower than average proportions. Assemblages up to *c.*65-70 m from fires generally have approximately similar distributions to *in situ* ones, being deficient in the smallest class of particles but having above average proportions of all other sizes. Only in the largest size class (>500 µm) is this general pattern broken, particles in this size class are only found in above average proportions at distances <40 m from fires. These relationships are discussed further in Sections 5.4.1 and 5.4.2.

## 5.4 Discussion

The analyses of charcoal dispersal on Tulach Hill produced a great deal of useful information about charcoal taphonomy, information which although specific to charcoal dispersal in moorlands in the first instance may be useful in wider contexts. The data confirms a number of established assumptions concerning charcoal dispersal but it also casts doubts upon others and suggests a number of new principles.

### 5.4.1 Charcoal production

The Tulach Hill fires produced unequal proportions of different sized charcoal particles. Smaller particles were produced in greater abundance than progressively larger ones. These findings are contrary to previously held beliefs which assumed that equal quantities of all particle sizes were produced by biomass fires (Patterson *et al.*, 1987) and have important implications in studies where particles are quantified according to their size, and either size class distributions or measures of charcoal particle area are used to infer fire proximity. When it is assumed that equal proportions of each particle size are produced, differences in the particle size distribution of a sedimentary assemblage are solely a function of differential dispersal processes. The presence of large particles is being taken as indicative of local fire activity or of high energy transport mechanisms (high wind velocities or surface runoff) (Clark, 1988a). However, size class production-bias imparts further complications into the equation.

The available evidence suggests that charcoal assemblages tend to be dominated by small particles, with decreasing quantities of progressively larger ones (Patterson, 1978; Patterson *et al.*, 1987; Carter, 1986). Could this be a consequence of the proportions in which they are produced? Over long distances dispersal-biases may be important in shaping the form of the sedimentary charcoal assemblage, small particles being transported further than larger ones and, therefore, being dominant in distant sedimentary assemblages despite to some extent the influence of production-bias. Over shorter distances (perhaps up to several hundred metres from the fire), however, production-bias may play a more influential role in determining the size class distribution of charcoal assemblages. Within the 'skip distance' (the maximum distance over which a particle of a given size is likely to be dispersed; Clark, 1988a) of the largest class of particles being studied, given the evidence of production bias from Tulach Hill, all charcoal assemblages will tend to have similar percentage size class distributions, whether they are within the boundary of the fire or at the limit of the largest particles dispersal-range because distance-decay curves for all particle sizes are parallel in form (Figure 5.5). The presence of large particles equate to 'local' fires as their presence indicates that a fire was within the particles skip distance, in accordance with traditional assumptions (*e.g.* Patterson *et al.*, 1987; Clark, 1988a). However, large particles are unlikely to comprise more than 1-2% of the total charcoal assemblage, regardless of how close the fire is, because of the production-bias inferred from the Tulach Hill data. Such an argument agrees with that of Battson & Cawker (1983) who expected to find that local fires would be characterised by high quantities of large particles but actually found that charcoal assemblages from nearby fires were swamped by small particles.

The presence of large particles in proportion to that dictated by production-bias would, therefore, indicate a relatively local fire, whilst lesser abundance may suggest a more distant source approaching or marginally beyond such particles typical range of dispersal. Charcoal assemblages dominated by small particles, however, are as likely to form near the parent fire as they are at considerable distance. It follows, therefore, that whilst assemblages of charcoal with high proportions of large particles may be relatively reliable indicators of proximity to a fire, the converse is not true. Charcoal assemblages dominated by small particles are not reliable indicators of an extra-local or regional source. A great deal of caution is therefore needed when interpreting charcoal source areas on the basis of size class distributions.

An insight into the importance of production-bias on sedimentary charcoal distributions can be gained by examining those obtained by previous studies. Patterson *et al.* (1987) noted that distributions of charcoal particles in arbitrarily assigned size classes generally adhere to a characteristic pattern. This pattern is illustrated by Patterson (1978) using over 27,000 charcoal particles from Squaw Lake, Minnesota tallied into size classes, see Figure 5.8.1 and Table 5.3.1. The Squaw Lake distribution is compared with the mean *in-* and *ex situ* size class distributions from Tulach Hill. Both the Squaw Lake and Tulach Hill data sets were quantified in six geometrically progressive size classes, and although the dimensions of the size classes differ (Squaw Lake = 86-172, 172-344, 344-688, 688-1376, 1376-2752, 2752-4472 $\mu m^2$; Tulach Hill = 992-1984, 1984-3968, 3968-7936, 7936-15872, 15872-31744, >31744 $\mu m^2$), this is of little consequence as it is the overall shape of the assemblages that is of interest.

Figure 5.8: Comparison of the proportions of charcoal particles in six size classes from Squaw Lake (Patterson, 1978) and Tulach Hill.

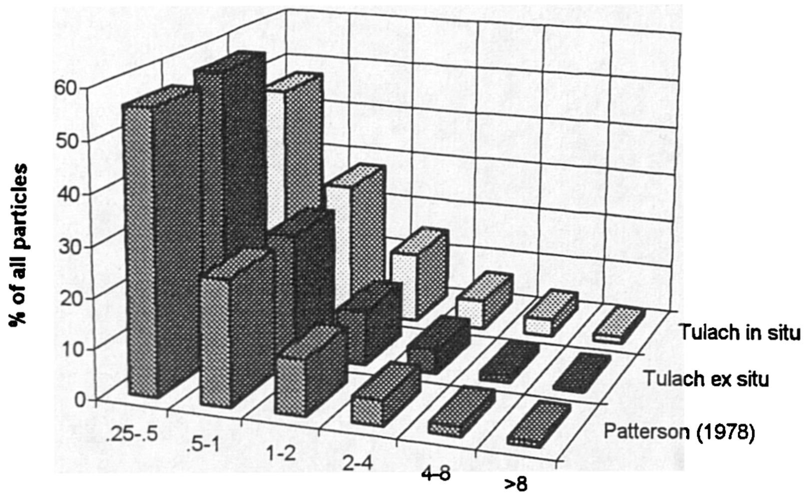



Table 5.3: Comparison of the mean proportions of charcoal particles (expressed as percentages) in six size classes from Squaw Lake (Patterson, 1978) and Tulach Hill.

| Grid squares | 0.25-0.5 | 0.5-1 | 1-2 | 2-4 | 4-8 | >8 |
|---|---|---|---|---|---|---|
| Patterson (1978)† | 56% | 25% | 11% | 5% | 2% | 1% |
| Tulach Hill *ex situ* | 57% | 25% | 11% | 5% | 1.5% | 0.5% |
| Tulach Hill *in situ* | 47% | 27.5% | 14.5% | 6% | 3.5% | 1.5% |

† The values were approximated from Figure 5 (Patterson *et al.*, 1987).

The Squaw Lake size class distribution is extremely similar to that of the *ex situ* assemblages from Tulach Hill, strengthening the assertion made by Patterson *et al.* (1987) that such characteristic size class distributions are common. Of further interest is the relatively close agreement of the percentage size class distributions between both the Squaw Lake and Tulach Hill *ex situ* assemblage distributions with the distribution of particles in size classes in *in situ* assemblages from Tulach Hill (taken to represent the actual proportions of charcoal produced by the moorland fires on Tulach Hill). Assemblages at source have slightly higher concentrations of all classes of larger particles and less than average very small ones, a feature which has been attributed to the differential dispersal distances of different sized particles (Section 5.3.2). However, the generally close relationship between the distributions of assemblages suggests that the differences in the proportions of charcoal produced at source are being translated to the sedimentary record. Production-bias appears to have had a profound effect on the size class distribution of the sedimentary charcoal records from both Tulach Hill and Squaw Lake. It is highly unlikely that the similarities between the distributions of the charcoal populations from the two sites, taken from totally different sedimentary media and analysed by different methods are the result of coincidence.

Further evidence of the possible magnitude of the influence of production-bias on sediment charcoal assemblages is provided by the substantial number of authors who have noted strong positive correlations between the quantities of charcoal across ranges of size classes (*e.g.* Mehringer *et al.*, 1977; Battson & Cawker, 1983; Carter, 1986; Patterson et al., 1987; Tipping *et al.*, 1993). For example, Mehringer *et al.* (1977) initially quantified charcoal from Lost Trail Pass Bog in eight size classes, and found that when particle abundance in the smallest size class was high, charcoal of all sizes was more common. As a consequence they converted their data into only two size classes, particles 10-25 μm (which contained the majority of particles) and those >25 μm, which were positively correlated at a high level of significance. The strong correlation between the size classes was attributed to being the result of charcoal particle breakage during sample preparation, the smaller particles being fragmented larger ones (Mehringer *et al.*, 1977). As a result they preferred to interpret only the larger fraction because they believed it was more representative of the original charcoal population.

Alternatively, it could be proposed that the correlation between the size classes is the result of production-bias, *i.e.* smaller particles are more abundant than larger ones because they were produced in greater abundance and the size classes are positively correlated for similar reasons. The relationship is perhaps particularly strong because the site is a peatland one, *i.e.* charcoal particles, like pollen, on bog surfaces are likely to be of a predominantly local origin and are resistant to mobilisation and redistribution (Gillette & Goodwin, 1974; Chamberlain, 1975) and the characteristic distributions of particles produced are likely to persist undisturbed in the charcoal assemblages.

Differential rates of pollen production by different plant species have long been acknowledged by palynologists (Pohl, 1937) and a number of correction factors have been developed to minimise the effects of production-bias on the interpretation of pollen diagrams (*e.g.* Iversen, 1949; Davis, 1963; Andersen, 1970). Similar considerations may need to be made when interpreting charcoal records so that the influences of production-bias are not erroneously interpreted as the product of dispersal-bias.

### 5.4.2 Dispersal during the fire event

Conventional wisdom and the evidence from Tulach Hill indicates that the majority of charcoal produced by fires is deposited rapidly, either during or very soon after the fire event (Patterson *et al.*, 1987). The dispersal mechanisms during fire events can, therefore, very important in determining the eventual distribution of the charcoal particle population, particularly when post-fire redistribution is limited. The principal mode of charcoal transport during fire events is through the atmosphere under the influence of gravity and wind (Clark, 1988a).

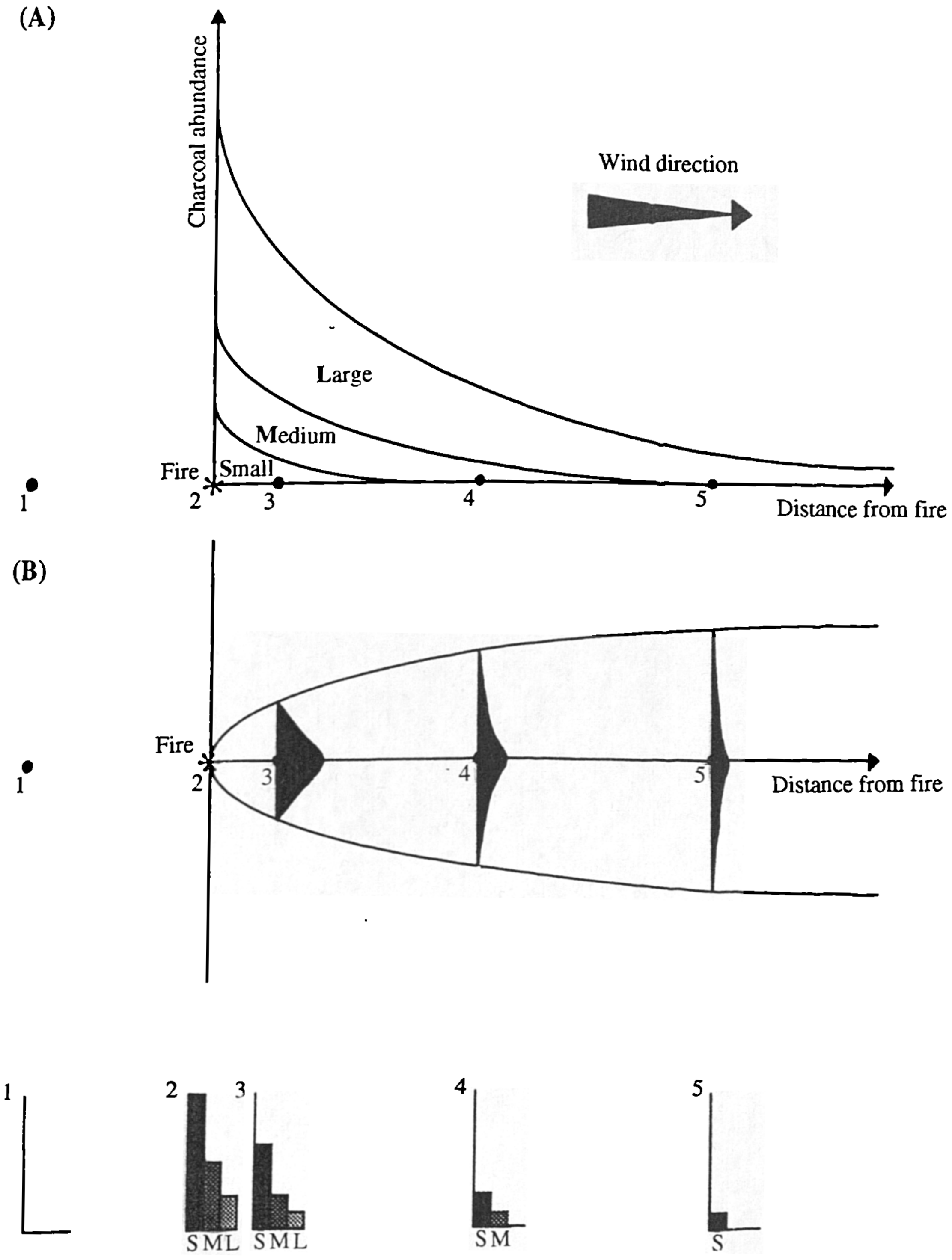
Vegetation fires vary greatly in form and intensity, from small low temperature ground fires to massive uncontrollable bush fires, and the spatial extent to which the charcoal particulates derived are dispersed varies accordingly. The height to which particles are lofted by convection currents formed by the fire and the wind direction and velocity during the fire are the two most important factors controlling patterns of dispersal (Chandler *et al.*, 1983). Elevation of particles by convection is important because deposition does not occur until the plume reaches the ground, and even quite small elevations of the source can strongly affect the proportion of particles travelling more than certain distances (Chamberlain, 1975). Particles lifted only several metres above the ground and not entrained within the convection column can in some instances be scattered hundreds of metres. Charcoal fragments lofted to a height of 1000 m could be transported tens to hundreds of kilometres (Clark, 1988a). Under the influence of strong winds dispersal distances are greatly extended. Dust sized particles (< 20 μm) can travel for hundreds or even thousands of kilometres in the atmosphere under the influence of the air-mass trajectories of zonal winds (Gillette, 1974). Much larger and heavier particles, however, are rarely lofted to sufficient altitudes for such transport to occur. They tend to have much shorter travel distances, in the order of hundreds of metres maximum, and are confined to the near-ground layer where the direction of travel is determined by the local surface winds (Foda, 1983).

Wind velocities during the Tulach Hill fires cannot be estimated from the muirburn maps, therefore, the effect of wind speed on dispersal distances cannot be fully discussed. Some of the effects of wind direction at the time of burning can, however, perhaps be estimated. The majority of charcoal is deposited down-wind of a fire, little is deposited laterally, perpendicular to the wind direction, or up-wind (Clark, 1982; Patterson *et al.*, 1987). This has important implications for the formation of charcoal records in sediment sinks. The vast majority of charcoal is deposited near to the fire, and though fires may occur close to sediment sinks unless they are down-wind they may receive little charcoal. The influence of wind direction is particularly important for short duration fire events during which the wind direction is unlikely to change markedly and distribute charcoal in all directions. However, the effects of the wind during fires may be negated if extensive post-fire redistribution by aeolian or fluvial processes occurs, as substantial quantities of charcoal may be subsequently dispersed in all directions.

Differential dispersal according to particle size plays an important role in determining dispersal patterns of charcoal particles. Particles are differentially distributed on the basis of their fall velocities a function of size, mass, shape and surface roughness, smaller, lighter particles are dispersed more widely than larger ones (Walker, 1971). However, for analyses of particle size distributions to be of use for determining fire proximity the differences between the sizes, and thus the fall velocities, of the particles in each of the size classes need to be marked. At Tulach Hill the differences between the mean particle sizes of the geometrically progressive size classes were substantial, illustrated by the divergence in the proportions of the smallest and larger particles between nearby and distant fires, even over the rather restrictive distance over which measurements were taken of only 300 m (Figures 5.7a-5.7f).

In the past large numbers of analysts have adopted ranges of particle size classes which have not been sufficiently great to resolve differential dispersal processes, the mean differences in particle size between classes has been so small that all particles are likely to have been transported very similar distances before deposition. Size classes must be at least geometrically progressive to ensure that differences between the mean particle sizes of particles within them are significant and enable any differences in dispersal to be resolvable.

### 5.4.3 Theoretical model of charcoal dispersal during a fire (Figure 5.9)



The model presented above (Figure 5.9) is based upon the findings of the Tulach Hill muirburn study and existing theories of microscopic particulate dispersal (Patterson *et al.*, 1987; Clark, 1988a). The first model of microscopic charcoal dispersal during biomass fires to be based directly upon actual charcoal data rather than pollen, sand and dust.

The model is highly simplistic, actual dispersal distances are not estimated and only three broad, undefined, charcoal particle size classes are presented (Small/Medium/Large). Wind dispersal during the fire is assumed to be the dominant mechanism of particulate diffusion, as suggested by the Tulach Hill data. In drier or more sparsely vegetated environments post-fire dispersal mechanisms (surface runoff and/or aeolian processes) may play an important role in particulate redistribution dispersal (Clark, 1983; Patterson *et al.*, 1987). For the purpose of the model wind direction has been assumed to be constant, although in real fires it may vary, especially during prolonged fire events, however, during muirburns which normally burn for less than an hour this assumption holds true. The fire in the model is represented as a point source, a simplification for the purpose of the model.

Charcoal dispersal is assumed to conform to the distance-decay principle, *i.e.* quantity and size of charcoal particles decrease as distance from the fire increases (Byrne *et al.*, 1977; Patterson *et al.*, 1987), the distance-decay curves used are leptokurtic in shape as noted at Tulach Hill. Small, medium and large particles are assumed to be produced in uneven quantities, progressively larger particles are produced in progressively smaller quantities. Figure 5.9a illustrates this relationship in two dimensions.

Figure 5.9b is a plan view of the fire event and resultant charcoal taphonomy, providing a theoretical appreciation of the spatial pattern of charcoal dispersal. The Gaussian plume model of dispersal, widely adopted for models of other microscopic particulates (Okubo & Levin, 1989), has been used to provide the best approximation of probable charcoal dispersal. The majority of charcoal is deposited directly down-wind, although with increasing distance particles diffuse more widely in a lateral direction. The histograms below the Gaussian model represent schematic approximations of both particle abundance and size class distribution for the five locations marked (1-5) on diagrams a & b.

Given a constant wind direction throughout the duration of the fire little or no charcoal is deposited up-wind, Histogram 1. Most of the charcoal is deposited within or very close to the boundary of the fire, Histogram 2 provides an indication of the size class distribution of particles for *in situ* assemblages. With increasing distance down-wind the differences in fall velocity of different sized particles control particle size distribution. Relatively close to the fire, Histogram 3, the abundance of particles across the range of size classes is reduced but the characteristic size class distribution imparted by production-bias is still discernible. Location 4 lies beyond the limits of dispersal of the largest particles and thus they are not represented in the sedimentary assemblage, Histogram 4. Likewise location 5 is beyond the range of both the large and medium sized particles and they are not represented in the charcoal record, only small particles are found in the sediments at such long distances.

As the model is based upon data from moorland fires it is most appropriate to moorland environments, however, the general principles may be more widely applicable.

### 5.4.4 Post-fire dispersal of charcoal by wind

After a fire a great deal of charcoal remains on the ground surface within and around the boundaries of the fire. Much of the material, particularly the finer microscopic fraction, is susceptible to mobilisation by aeolian processes. This is particularly true under dry conditions where adhesive forces between the charcoal and soil particles are minimal (Chamberlain, 1975; Foda, 1983).

The processes of saltation, suspension and traction are likely to be the dominant mechanisms of post-fire charcoal transport by aeolian forces (Clark, 1988a). Green (1981; 1982), Byrne *et al.* (1977), Clark (1988a), Clark *et al.* (1989), Martin (1994), Mehringer *et al.* (1977), Odgaard (1993), Terasmae & Weeks (1979), Swain (1978), Gajewski *et al.* (1985) and MacDonald *et al.* (1991) all believe aeolian dispersal of charcoal to be predominant over fluvial processes.

Particulates begin to blow when the resultant of the shearing stress, adhesive and gravitational forces is sufficient to lift individual particles from the ground (Chamberlain, 1975). Pollen slide sized charcoal, 90% of which is 5-20 μm in length (Patterson *et al.*, 1987), are not readily entrained by turbulence because cohesive forces bind them to each other and to soil aggregates, however, if they are suspended they can be dispersed widely (Clark, 1988). Charcoal particles in the 130-150 μm size range are readily lifted by wind speeds of only about 20 m/s and as wind speeds exceed this threshold the rate of particulate removal increases rapidly. Larger particles can be picked up by surface winds but their relatively high mass dictates that they are soon redeposited and are only moved short distances (Clark, 1988a). Saltation is probably the main process by which medium to large particles are dispersed, indeed Maltby *et al.* (1990) observed substantial movements of ash and fine peat granules saltating and in suspension in winds following a severe moorland fire on the North York Moors.

The aeolian processes described above are most effective under dry conditions because charcoal particles are much heavier when wet and soil surface moisture has a very high retention capacity (Foda, 1983). Such processes are also only effective on bare soils and ground surfaces, amongst even sparse vegetation soil particulates rarely blow even in high winds because the shearing stress on the soil is too low (Chamberlain, 1975). Aeolian distribution processes are thus only prevalent under dry conditions and for a restricted period after the fire until vegetation regeneration has occurred.

### 5.4.5 Post-fire dispersal of charcoal by water

The dispersal of charcoal following fires by fluvial processes has been cited by many as a major process through which charcoal is redistributed (Swain, 1973; Blong & Gillespie, 1978; Cwynar, 1978; Clark, 1983; Rummery, 1983; Patterson, 1978), although others disagree believing its importance to be overstated (Clark, 1988a; Green, 1981; 1982; Byrne *et al.*, 1977; Clark *et al.*, 1989; Martin, 1994; Mehringer *et al.*, 1977; Odgaard, 1993; Terasmae & Weeks, 1979; Swain,- 1978; Gajewski *et al.*, 1985; MacDonald *et al.*, 1991).

There is, however, much debate over the effect that surface fires have upon the infiltration properties and hence the surface runoff characteristics of soils. Auten (1933) and Wahlenberg *et al.* (1939) found increased infiltration capacities in forest and field soils following fires, Veihmeyer & Johnson (1944) and Burgy & Scott (1952) found no reduction of infiltration in Californian chaparral soils, and Rowe (1941) noted a reduction of 90-95% in the infiltration capacity of woodland chaparral soils after burning. In moorland studies, Kinako (1975) found that infiltration on burned plots was *c.*50% greater than on unburned ones, whilst in contrast, Heyward & Barnett (1934), Heyward (1936), Surman & Halls (1955), Hanks & Anderson (1957), McMurphy & Anderson (1965), Mallik (1982) and Mallik *et al.* (1984) all found substantial decreases in water infiltration into moorland soils following heather burning. Mallik *et al.* (1984) suggested that the reduced infiltration capacity was due to ash particles on the soil surface clogging the soil pores in the upper soil layer, their measurements of soil moisture retention properties and porosity support their view.

The effects of such reduced infiltration capacity could be marked. Moore (1978) reported an increase in runoff of 60% in a Minnesota lake catchment following a fire, and both Swanson (1981) and Arnett (1980) observed dramatic increases in soil sediment loading of streams at peak discharges following fires. Clark (1983) monitored the charcoal content in water samples from the Wallagaraugh River both before and after a major fire in its catchment and found that the only time significant quantities of charcoal were washed into the river was in the first post-fire rainfall event, with the highest concentration at the beginning of the event. Maltby *et al.* (1990) also observed considerable erosion of surface debris by water under storm conditions, erosion from bare surfaces exceeding that under mature heather stands by at least twenty times. In contrast, however, Imeson (1971) noted erosion due to solution, eluviation and wind erosion, but surface runoff did not occur even after heavy rain.

It is clear that there is no unequivocal consensus over the issue of whether biomass fires reduce the infiltration capacity of soils, and therefore promote increased surface runoff and possible enhanced erosion. The evidence cited has, however, been taken from a wide range of environments with quite different soil and fire characteristics. The majority of evidence from studies of moorland burning suggests that in the majority of cases burning may well reduce the infiltration capacity of the surface soils making it more susceptible to surface wash and erosion (Heyward & Barnett, 1934; Heyward, 1936;

Surman & Halls, 1955; Hanks & Anderson, 1957; McMurphy & Anderson, 1965; Mallik, 1982; Mallik *et al.*, 1984).

### 5.4.6 Post-fire charcoal dispersal on moorland

The following discussion provides a summary of the effects and implications of post-fire dispersal of charcoal on moorland by aeolian and fluvial processes. Widespread, large-scale, secondary dispersal of charcoal following muirburns is believed to be of perhaps limited importance in comparison with the initial dispersal of particulates during the fire. It is accepted that an increase in particulate redistribution and erosion following disturbance of vegetation cover by fire might be expected since the balance of the ecosystem is upset (Imeson, 1971), however, the data from Tulach Hill and reviewed literature suggests that any dispersal occurring is likely to be over relatively short distances. The extreme weather conditions of the British Isles provide strong potential for erosion of unprotected, bare ground (McVean & Lockie, 1969), however, only after particularly high intensity, uncontrolled fires are moorland soils left completely bare and exposed (Gimingham, 1960; Radley, 1965), controlled muirburns rarely remove all of the surface vegetation and accumulated litter (Whittaker & Gimingham, 1962). Most muirburns tend to leave considerable quantities of partially burnt *Calluna* and litter on the soil surface, and as the soil surface itself is rarely burned erosion from small muirburns may be relatively restricted.

Kinako and Gimingham (1980) conducted a study to establish the magnitude of soil and charred particulate losses from muirburns. Movements of ash and small pieces of charcoal were noted within burnt patches, due mainly to the wind, although fluvial processes may also have played a minor role. Most of the particulate redistribution was movement of particles on a very restricted scale within-the burned patch itself, and in a predominantly down-slope direction. Eroded particles were only moved very short distances from small muirburns into neighbouring vegetated areas because the moorland vegetation was very dense (Kinako & Gimingham, 1980). Evans & Moore (1985) illustrated the extremely restricted nature of *Calluna* pollen dispersal within heather swards, presumably the same is true for microscopic charcoal particles. Charcoal particles may be dispersed more widely around large burnt patches as greater winds generate more energy to entrain, loft and distribute particulates.

Movement of particulates within burnt patches continues until regeneration of vegetation cover restores stability. This can take between 15-20 months (Kinako and Gimingham, 1980) and 3-5 years (Radley, 1965) depending upon the severity of the fire and whether heather regenerates from stem bases or seed. Heather and the dense fabric of litter and moss which forms beneath it represents an almost impenetrable barrier to charcoal movement either by aeolian or fluvial processes (Maltby *et al.*, 1990). Charcoal deposited beneath heather is, therefore, very unlikely to be remobilised and redistributed.

### 5.5 The lacustrine sediment charcoal record in moorland contexts

The concepts of charcoal taphonomy discussed throughout this chapter can be used to provide some appreciation of how lakes within moorland catchments record fire histories. This is of particular importance in this research project as the following two chapters deal with lacustrine charcoal records from moorland environments.

#### 5.5.1 Charcoal production and the nature of the sediment charcoal record

Muirburns are relatively small, burn for short periods of time, and are typically distributed widely over moorland catchments. Charcoal is produced in large quantities, but the total amount of charcoal produced is the sum of many small and scattered sources. On well managed moors where burning is an annual process, and considering the restricted resolution available in most lake sedimentary sequences, charcoal production and deposition might be best practicably considered as continual processes.

Moorland catchments rarely experience single, large-scale fires which burn most of the catchment separated by prolonged periods of limited fire activity, as is the case with most environments in which fossil charcoal analyses are conducted. The sediment charcoal record of lakes in moorland catchments are rather more complex. Individual peaks of charcoal abundance in moorland sediments are unlikely to represent individual fire events, however, it may be possible to detect and reconstruct broad changes in the magnitude and frequency of burning activity within catchments. The limitations imposed by the nature of charcoal production, the resolution of the sediment record, and the sampling strategy employed need to be considered extremely carefully during interpretation.

### 5.5.2 Charcoal 'source area'

The concept of 'source area' is well established with respect to pollen, representing the area from which the dominant component of the sedimentary assemblage is derived (Prentice, 1985; Sugita, 1993; Jackson, 1993). The approximate radius around the sediment sink from which the charcoal is derived needs to be known before microscopic charcoal records from a sediment sequence can be effectively interpreted. The Tulach Hill data suggests that the majority of charcoal entering a moorland lake basin is likely to have originated from within an approximate radius of 70-80m. A component of the smaller charcoal particles may be derived from greater distances, especially in larger lakes with greater capacities for capturing extra-locally or regionally derived charcoal (Jacobson & Bradshaw, 1981; Clark, 1988a). However, as demonstrated for pollen by Sugita (1993) the majority of charcoal, in even relatively large diameter lakes, is likely to have originated from predominantly local sources (See Section 2.3.5).

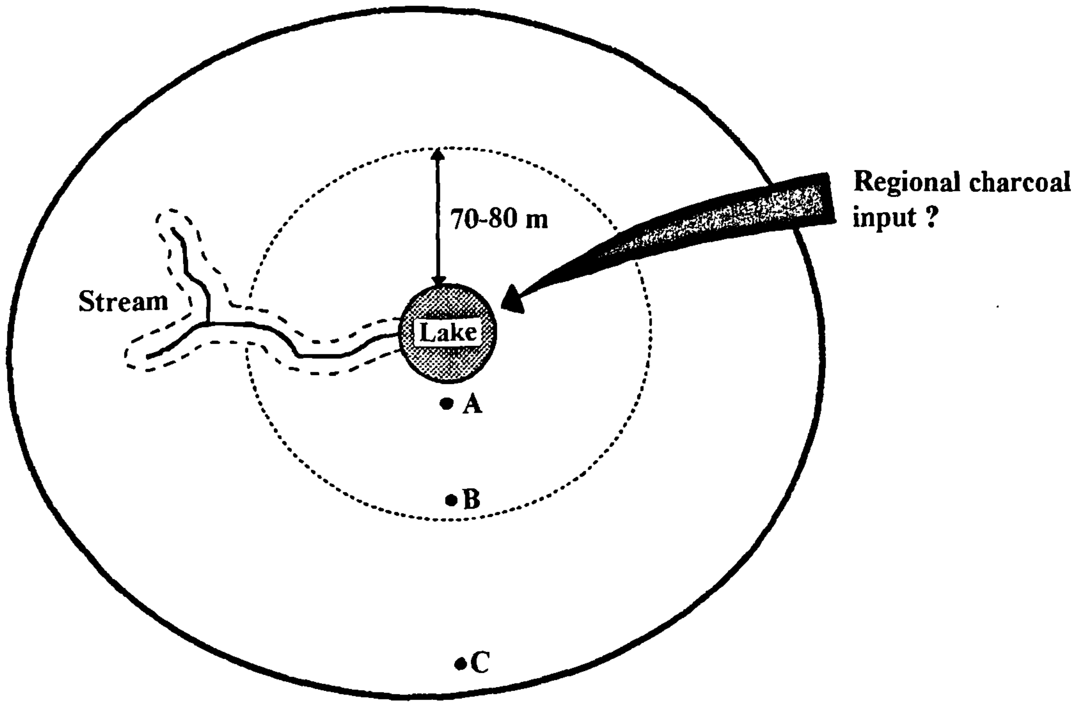
The Tulach Hill data suggest that for small muirburns on moorland atmospheric dispersal of charcoal during fires may be the most important means of charcoal transport. Wind direction during fires is, therefore, a very important factor controlling dispersal and representation in sediment assemblages, fires very close to a lake may only deposit large quantities of charcoal directly into the basin if the wind is blowing toward it, little will be deposited at the site if it is up-wind of the source fire. Large numbers of fires burned under unfavourable wind conditions may not be represented in the charcoal record despite being within 70-80m of the lake. As a consequence, despite relatively high charcoal production in moorland environments, the concentrations of charcoal in the sediments of moorland lakes may be relatively low. Alternatively, a single or a small number of fires burning close to a lake with favourable wind conditions could deposit substantial quantities of charcoal in it. It may, therefore, prove very difficult, perhaps even impossible, to reconstruct anything more than very poorly defined fire histories in such environments.

Post-fire redistribution of charcoal is believed to be of minimal importance. The only time that post-fire dispersal is likely to contribute substantial quantities of charcoal to lakes in moorland catchments, even when the slopes surrounding the lake are fairly steep, is when fires extend right up to the lake shore. Otherwise the dense heather and litter around lakes acts as a filter preventing transport of particulates from entering the lake by either aeolian or surface hydrological processes (Terasmae & Weeks, 1979; Tolonen, 1983). Burnt patches on the lake shore could, however, release substantial amounts of charcoal into the lake for substantial periods after the fire until the soil surface is stabilised by vegetation regeneration.

Studies of stream inlet sediments have indicated that particulates can be transported to lakes by catchment streams (Blong & Gillespie, 1978; Rummery, 1983). Some charcoal may be deposited in moorland lakes by such processes, especially when large networks of tributaries exist, or when the areas immediately surrounding streams are burned. However, inputs of charcoal to streams is likely to be minimal when they are surrounded by dense vegetation as little charcoal will enter them. Clark (1983) also indicated that significant amounts of charcoal are only transported in streams during restricted periods immediately after fire events.

Figure 5.10 is a highly stylised model summarising the hypothesised recruitment of charcoal into moorland lakes developed from the Tulach Hill data and the available literature. An approximate 70-80m radius is marked around the lake with a dotted line. This is the approximate area from within which the majority of charcoal is hypothesised to be derived (see Section 5.3.2). Some charcoal may enter the lake from fires in the rest of the catchment given strong winds blowing toward the lake during combustion, although this component is believed to be relatively insignificant in comparison with that from within the 70-80m source area. Likewise a very minor component of predominantly small particles may also be derived from outside the catchment.

Figure 5.10: Schematic model of the charcoal taphonomy in a moorland lake catchment.




Three locations A, B and C have been marked on the diagram as a means of illustrating the hypothetical importance of inputs of charcoal from different areas of the catchment. The relative inputs of charcoal from fires at locations A, B and C are dependent upon the wind strength and direction during the fire. Even in a strong wind blowing toward the lake it is hypothesised that little charcoal from location C would enter the lake. In the same wind more charcoal would enter the lake from a fire at location A in comparison with location B but both could potentially contribute significant quantities of charcoal. If the wind direction during the fires were away from the lake hardly any charcoal would be deposited in the lake, even from location A.

The zone marked around the tributary stream represents the theoretical catchment area of charcoal particulates which it could possibly transfer to the lake. The zone is restricted to the immediate banks of the stream, because dense vegetation is likely to filter and retain charcoal particulates preventing them entering the stream from any significant distance.

The model presented above is highly simplistic and relates primarily to relatively small lakes, in homogeneously vegetated (*Calluna*-dominated), gently undulating, moorland catchments. It is acknowledged that all sites have unique characteristics and that the specific fire regimes, dominant dispersal processes, and catchment characteristics of each individual site studied must be considered carefully before applying the principles of the model. However, the model does provide a means of summarising the findings of the Tulach Hill charcoal taphonomy study and provides a basis for estimating source areas of charcoal deposited on the lake sites used in the following chapters.

## 5.6 Conclusions

### 5.6.1 Charcoal production

Moorland fires produce variable quantities of charcoal. The reasons behind this have not been determined in this study but it is likely that variations in charcoal production are a function of fuel and fire characteristics, *i.e.* fuel volume, fuel composition, fuel condition, fire temperature, fire duration *etc.* The implications of this for the palaeoecologist are important as variations in volumes of charcoal in samples from cores need not necessarily reflect differences in fire proximity but may be the product of differential production processes.

Muirburn fires do not produce equal quantities of different sizes of microscopic charcoal particles. Smaller charcoal particles are produced in significantly greater quantities than progressively larger ones. These inequalities in production, termed 'production bias', have important implications for the interpretation of charcoal records, especially when the charcoal has been quantified on the basis of particle size with the intention of using the size class distribution of assemblages as a proxy measure of fire proximity. Traditionally differentials in the proportions of different sized particles in charcoal assemblages have been interpreted as being the product of differences in propensity for dispersal, *i.e.* charcoal assemblages composed of predominantly small particles were assumed to be of extra-local or regional origin whilst the presence of larger particles suggested local origins. Small charcoal particles are more likely to be dispersed more widely than large ones but the fact that smaller particle are produced in far greater quantities than larger ones suggests that even locally produced assemblages will be dominated by smaller particles. Both 'production bias' and 'dispersal bias' contribute to the final form and size class distribution of sediment charcoal assemblages

### 5.6.2 Dispersal of microscopic charcoal around muirburns

The analyses of charcoal taphonomy on Tulach Hill suggest that charcoal dispersal around muirburns is relatively restricted. The results from Tulach Hill illustrate that whilst small numbers of charcoal particulates can be transported up to and possibly beyond 300m from burns, the vast majority are deposited within a 70-80m radius of source fires. The implications of these findings for palaeoecologists are that charcoal records in moorland contexts are likely to reflect histories of local fire activity, although a small component of any given sediment charcoal assemblage may have extra-local or regional origins a local fire signal should predominate.

The analyses on Tulach Hill also highlighted the importance of the wind direction at the time of a fire as an agent of particulate dispersal. The vast majority of charcoal produced by muirburns was inferred to have been deposited down-wind of source fires, very little was deposited up-wind or perpendicular to the direction of wind flow. This has important implications for palaeoecologists utilising sediment charcoal records. The situation may arise whereby sediment cores from locations in close proximity to but up-wind of fires may not record them in their fossil charcoal profiles. This concept is not new to charcoal analysts (*e.g.* Clark, 1982; Patterson *et al.*, 1987) but the Tulach Hill data serves to reinforce the possible influence of the wind at the time of a fire as an agent of charcoal dispersal.

# Chapter 6: Peat Erosion


## Abstract

Microscopic charcoal analyses of sediment cores were used to reconstruct long-term fire histories for seven moorland lake catchments in the UK and Ireland known to have experienced peat erosion over the past millennium. Redundancy analysis (RDA) was used to test the relationship between peat erosion histories of the catchments, inferred from LOI profiles, and the reconstructed fire histories in an attempt to determine whether catchment burning may have caused the initiation of past erosion events. The results obtained suggest that burning may have been a significant factor contributing toward erosion inception at only one of the seven sites studied.


## 6.1 Introduction

Fire has played an important role in the development and maintenance of the heather-dominated vegetation of British and Irish moors and blanket bogs over extended periods of time (Gimingham, 1970). Controlled burning has been practised for many centuries in order to promote and sustain heather dominance for herbivores, particularly sheep, deer and grouse (Muirburn Working Party, 1977; Gimingham, 1975). Whilst there is little evidence to suggest that well controlled periodic burning of vegetation is deleterious to moorland communities (Gimingham, 1972; DOAS, 1976), uncontrolled fires can have profound impacts. Ecological studies following large-scale, uncontrolled contemporary moorland fires have shown that they can have extremely detrimental effects on vegetation cover, and initiate prolonged episodes of erosion (*e.g.* Imeson, 1974; Maltby, 1980; Maltby *et al.*, 1990; Thomas *et al.*, 1994).

Approximately 8% of the land surface of the British Isles (30% of Scotland) are peat covered (2.68 M ha) of which the majority is upland blanket peat (Taylor, 1983). Extensive erosion is a considerable problem in all British and Irish peatland areas, *i.e.* the Pennines and Northern Uplands of England (Conway, 1954; Bower, 1960; Tallis, 1964, 1965), Scotland (Stevenson *et al.*, 1990; Grieve *et al.* 1994), Northern Ireland and Ireland (McGreal & Larmour, 1979; Alexander *et al.*, 1985). Peat erosion constitutes a considerable problem for upland management and conservation, large tracts of grouse moor and livestock grazings are being lost, water storage capacities of reservoirs are been reduced by peat in wash, losses of heather-dominated vegetation have led to a reduction in flora and fauna characteristic of moorland, and the amenity value of moorland is being eroded along with the footpaths and scenery (Phillips *et al.*, 1981).

There is obviously a great need to identify the processes which initiate the erosion of peat masses so that long-term management strategies can be formulated (Bradshaw & McGee, 1988). Investigations seeking to elucidate the timing and causes of peat erosion events in Britain and Ireland have generally been unable to isolate the specific causes, however, a number of hypotheses have been outlined: climate change (Conway, 1954; Tallis, 1965, 1973, 1985, 1987); the development of inherent instability in peat masses (Bower, 1961, 1972; Alexander *et al.*, 1986); anthropogenic effects such as burning, grazing, trampling and land drainage (Radley, 1962; Shimwell, 1974; Tallis, 1981, 1987; Battarbee *et al.*, 1985); air pollution (Ferguson & Lee, 1993; Tallis, 1985); and a combination of the above factors (Phillips *et al.*, 1981).

A considerable number of studies cite disturbance by fire as a possible major cause of peat erosion (*e.g.* Tallis, 1964; Tallis & Switsur, 1983; Stevenson *et al.*, 1990). Fire has great potential for destroying and removing surface vegetation, and as highlighted by Dunham (1963) 'where the cover of living vegetation is destroyed, erosion of the underlying soft peat will inevitably begin'. Stevenson *et al.* (1990) in particular stress the need for extended fire histories from eroded catchments in order to elucidate the possible relationship between past fire-management of peatlands and their erosion.

The present study was carried out to assesses the extent to which changing burning regimes in the catchments of seven British and Irish lakes might have caused the initiation of peat erosion. Palaeoecological analyses of lake sediment cores are used to reconstruct the erosional and burning histories of the catchments over the recent past (up to 1100 years BP) and multivariate statistical methods are used to assess whether a significant relationship existed between erosion and burning intensification. Alternative hypotheses of erosion initiation at the sites are also considered.

## 6.2 Outline of methodology

The following methodology was devised in an attempt to determine whether fire activity in upland moorland catchments had been responsible for initiating erosion of catchment peats. The rationale for site selection is outlined in Section 3.1.2.

- Short sediment cores (*c*.80 cm) were extracted from Lough Muck, Blue Lough, Round Loch of Glenhead, Loch Teanga, Loch Tanna, Loch Na Larach and Llyn Conwy.
- Percentage loss-on-ignition (LOI) profiles, a proxy measure of peat erosion activity in the catchment (Bradshaw & McGee, 1988), were derived for each site.
- Microscopic charcoal analyses were performed by the method outlined in Chapter 3 to provide extended catchment fire histories.
- Redundancy analyses (RDA) and Monte Carlo permutation tests (Lotter & Birks, 1993; Korsman *et al.*, 1994) were used to assess whether catchment fire activity had a significant effect as a possible cause of peat erosion in the catchments.

### 6.2.1 Site selection rationale

The seven UK and Irish lake catchments selected for study were chosen because they fulfilled a number of important criteria (see Figure 3.2 for the location map and Section 3.1.2 for summary information on the individual sites). Each has obvious evidence of either present or past peat erosion in their catchments. All are headwater lakes, chosen in an attempt to help define the source area of charcoal entering the lake sediments. Palynological studies have suggested that headwater lakes, with limited drainage networks, have small pollen source areas and, therefore, sediment records are likely to reflect local rather than extra-local pollen spectra (Peck, 1973; Bonny, 1976; Jacobson & Bradshaw; Birks *et al.*, 1990). A similar line of reasoning is adopted for microscopic charcoal, *i.e.* that the lake sediment records of the lakes studied should contain charcoal of a predominantly local origin, and thus provide histories of fire activity within their respective catchments (see also Chapter 5). The distribution of the sites from N Wales through to the north of Scotland and into Ireland and Northern Ireland allows some assessment of whether regional patterns, both in the timing and possible causes of peat erosion, exist.

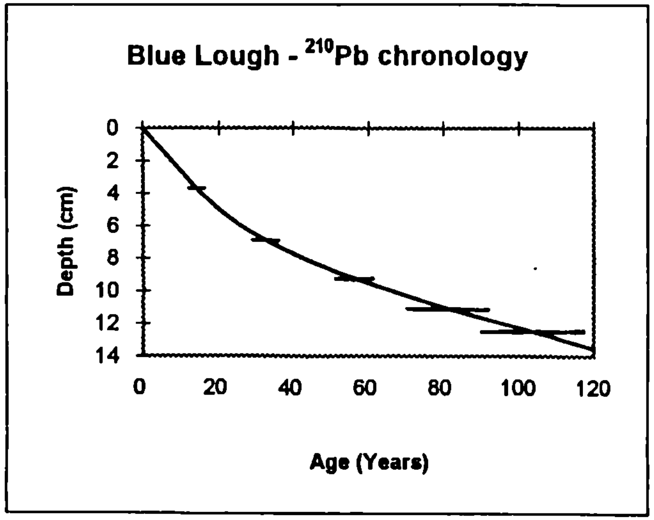
### 6.2.2 Dating of the sediment cores

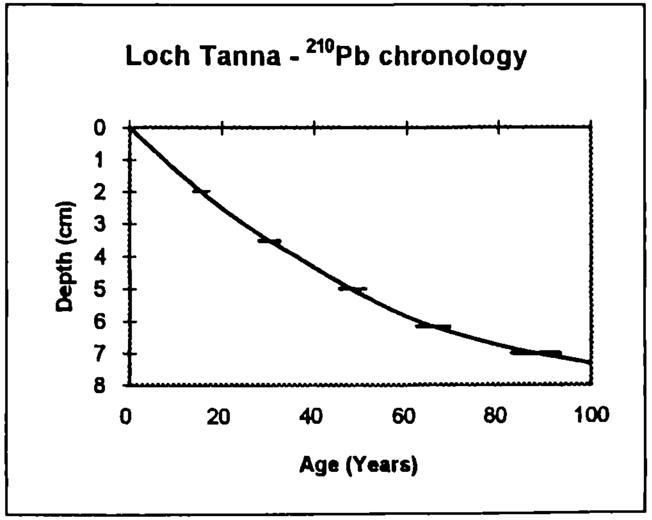
Chronologies for the upper sediments of all the cores were constructed using the $^{210}Pb$ CRS model (Appleby & Oldfield, 1978). Figures 6.1 and 6.2 present the $^{210}Pb$ age/depth profiles for the seven sites (the chronologies and accumulation rates are presented in tabular form in Appendix 5). The Round Loch of Glenhead and Loch Teanga cores were also dated using $^{14}C$ methods (Jones *et al.*, 1987; Jones *et al.*, 1989). Nineteen $^{14}C$ dates on bulk peat samples were conducted on the Round Loch of Glenhead core and ten were performed on the Loch Teanga core (Appendix 6).

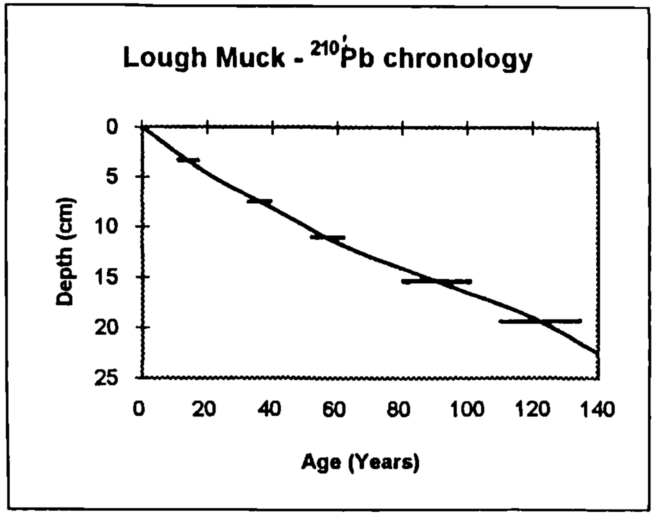
The dates of the loss on ignition increases which lie below the portions of the cores dated directly by $^{210}Pb$ methods were estimated by extrapolation. It is acknowledged that such a method is built upon the assumption that accumulation rates have remained relatively constant over extended periods, but without additional dates further down the cores it represents the best available method. The $^{210}Pb$ derived age/depth profiles for Lough Muck, Loch Na Larach and Llyn Conwy which show strong, statistically significant, linear relationships and thus the $^{210}Pb$ chronologies were extrapolated to the core bases using a simple linear regression model. The $^{210}Pb$ chronologies for Blue Lough and Loch Tanna, however, display exponential age/depth profiles, for these sites extrapolations were based on the lowermost portions of the curves where significantly linear relationships exist. The dates estimated in this fashion have potentially large error margins, with perhaps correspondingly greater errors on progressively earlier dates, therefore, all dates should be taken as approximations with minimum errors of at least ±50 years.

At Round Loch of Glenhead and Loch Teanga where $^{14}C$ dates were available in addition to $^{210}Pb$ chronologies the dates of LOI increases were estimated by regression after amalgamating the two chronologies. At Round Loch of Glenhead, however, a number of the dates are believed to have been contaminated by older carbon (Stevenson *et al.*, 1990) and thus are unreliable. Consequently only the dates from the lower most

Figure 6.1: $^{210}Pb$ age/depth curves for Blue Lough, Loch Tanna, Lough Muck and Loch Na Larach.



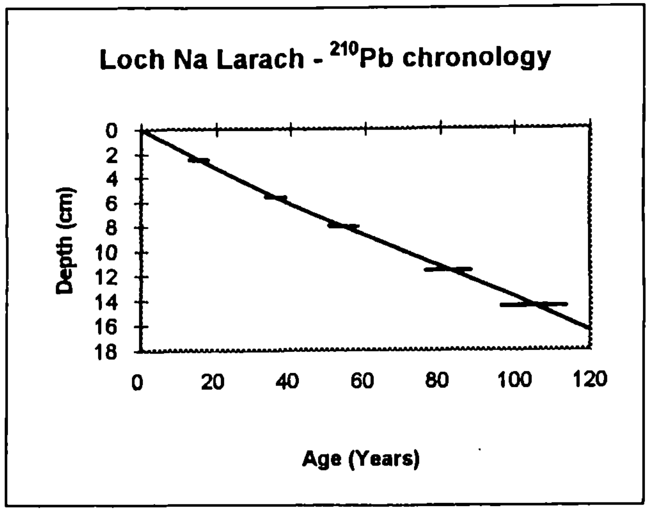
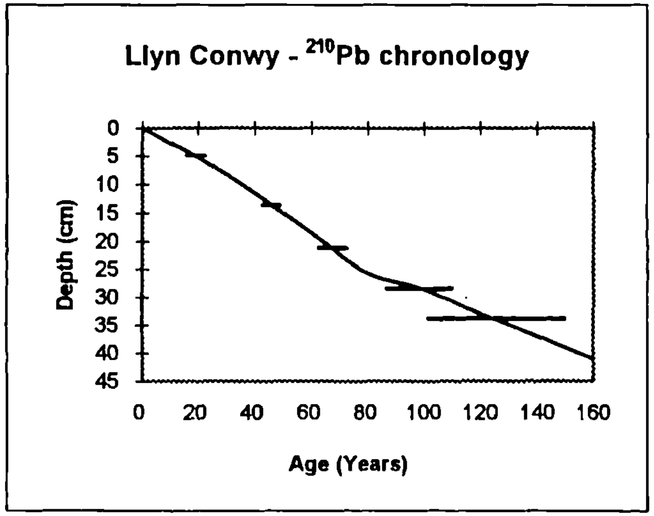
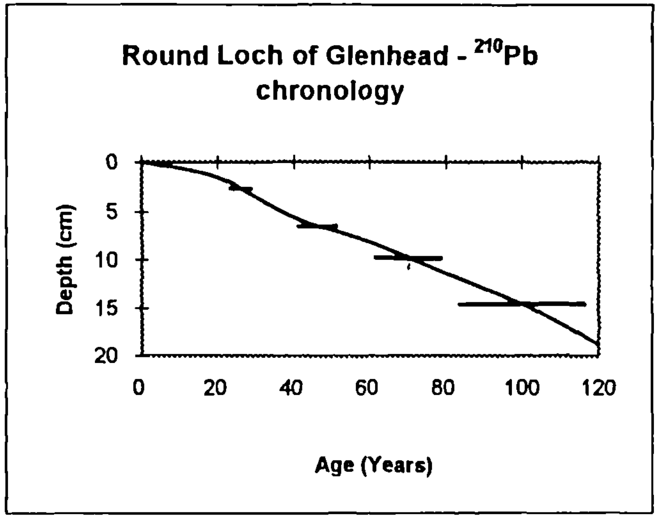
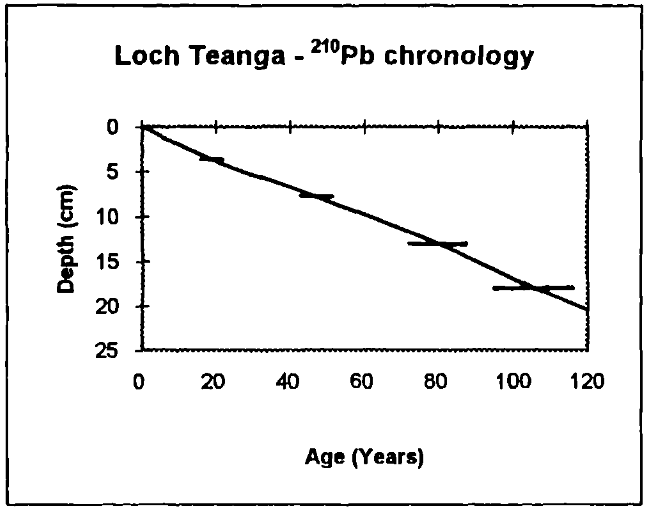



Figure 6.2: $^{210}Pb$ age/depth curves for Llyn Conwy, Round Loch of Glenhead and Loch Teanga.



sections of the core, and the youngest dates which appear to be free from older carbon errors, were used in the age estimations (Stevenson *et al.*, 1990). The dates estimated in this manner are again subject to considerable sources of error and thus must be treated with caution.

### 6.2.3 Statistical analyses

The possible influence of fire activity as a cause of peat erosion in the catchments of the seven lake sites studied was assessed by canononical ordination techniques (Birks & Lotter, 1993; Korsman *et al.*, 1994). The charcoal data, as proxy measures of reconstructed fire activity, were used as 'environmental' or predictor variables to explain statistically the catchment erosion records, represented by the reconstructed % LOI profiles. Detrended canononical correspondence analysis (DCCA) was used to ascertain whether linear (redundancy analysis; RDA) or unimodal (canononical correspondence analysis; CCA) ordination methods were appropriate (Hill & Gauch, 1980). The gradient lengths of the first DCCA axis for all of the LOI profiles were short (<1.6 SD) and so RDA was used (ter Braak & Prentice, 1988). The statistical significance of the RDA analyses were assessed by restricted Monte Carlo permutation tests for stratigraphically ordered data (ter Braak, 1990a), four hundred and ninety-nine permutations were used for each test (John Birks, pers. comm.). The computer program CANOCO 3.12 (ter Braak, 1990b) was used to perform all calculations and analyses.

## 6.3 Results

### 6.3.1 Loss-on-ignition profiles

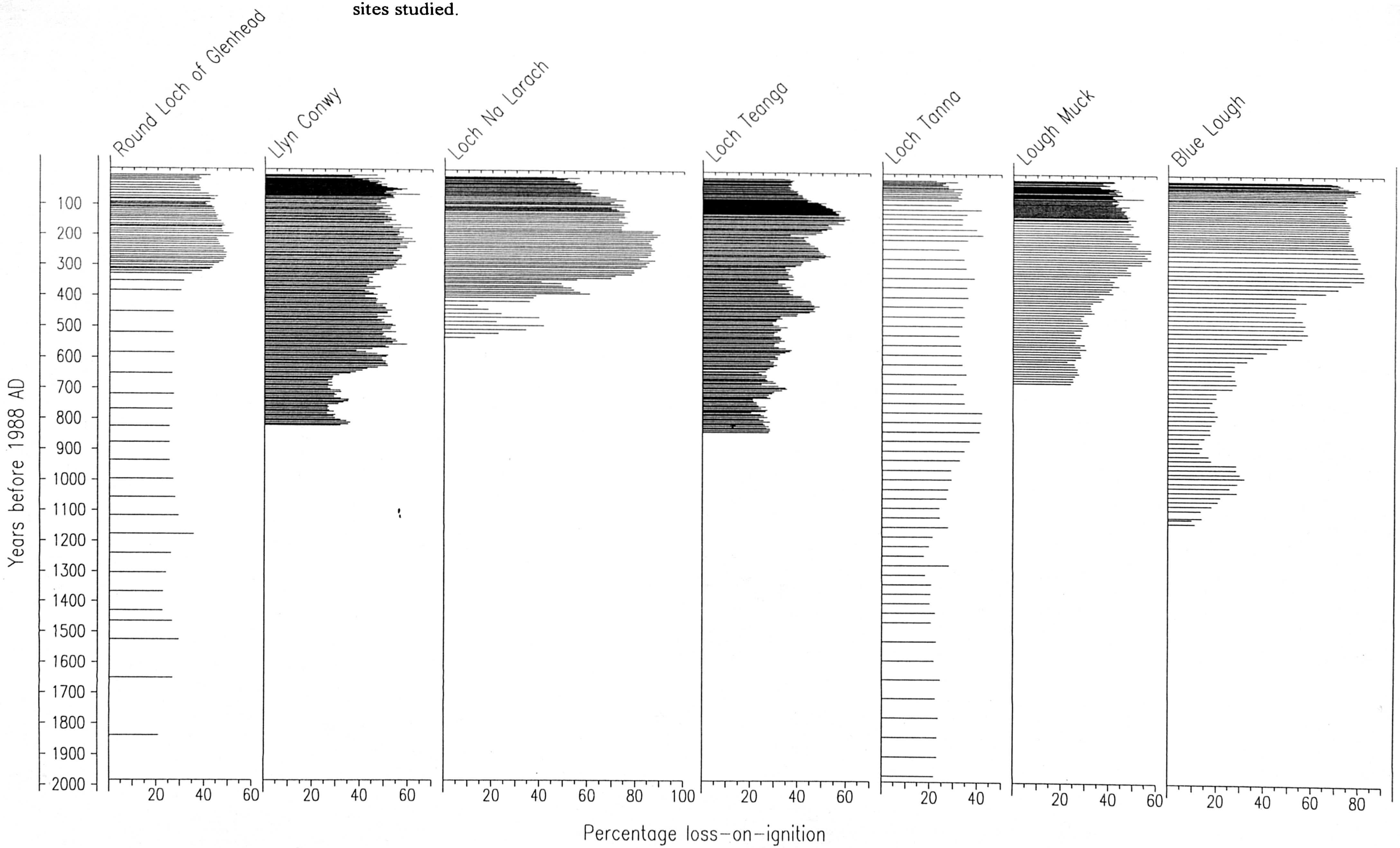
Loss on ignition (LOI) measurements provide an accurate technique for determining the organic matter content of sediment (Dean, 1974). LOI measurements of lake sediments have been used by a number of authors as proxies for catchment peat erosion (*e.g.* Bradshaw & McGee, 1988; Stevenson *et al.*, 1990; Stevenson *et al.*, 1992), because in unproductive acidic lakes in catchments dominated by blanket peats marked increases in the % LOI of the lake sediment record are almost certainly due to accelerated erosion of surrounding catchment peats (Bradshaw & McGee, 1988: Stevenson *et al.*, 1990).

Lake sediment records from all seven of the lakes studied show evidence of erosion episodes during the past 1100 years (Figure 6.3), and with the exception of Loch Teanga all have experienced at least one major episode of erosion within the past 700 years. In the Round Loch sediment core LOI values increase abruptly between 49-40 cm depth (*c.*1650-1700 AD) from 30% to 50%, a feature seen in a number of other replicate cores from the loch (Stevenson *et al.*, 1990). A number of much smaller short-term erosional events prior to the main episode event appear to be minor in comparison. The main period of erosion intensification in the Llyn Conwy catchment occurred at a depth of between 139-133 cm (*c.*1300-1400 AD), indicated by the increase in LOI values from 30-50%, in a similar manner to the Round Loch profile. A number of less significant, smaller scale erosion events occurred both prior to and following the main episode of erosion intensification. Loch Na Larach experienced several distinct periods of erosion, the two most marked episodes were initiated between 64-58 cm (*c.*1550-1600 AD) when LOI values rose from 15-60% before stabilisation. and then between 52-43 cm (*c.*1650-1700 AD) when LOI values rose again from 40-85%.

Loch Teanga's LOI profile exhibits evidence of a complex erosional history characterised by numerous short episodes of catchment erosion followed by stabilisation and subsequent renewal of erosion activity. Amongst the numerous peaks in the LOI record three are of greatest significance, between 89-85 cm (*c.*1500-1550 AD) LOI values rose sharply from 30 to 50% before falling and remaining relatively constant until 56 cm (*c.*1700 AD) with renewed erosional activity, the final major erosion event was initiated at *c.*34 cm (*c.*1800 AD). The LOI record from Loch Tanna is much less striking than the others considered here. The increase in LOI values was very gradual and even during the periods of inferred maximum erosion between 39-29 cm (*c.*900-1200 AD) and 10-7 cm (*c.*1800-1900 AD) LOI values only reach *c.*40%.

The Lough Muck LOI profile is characterised by a gradual increase in erosion activity between 60 cm (*c.*1500 AD) (LOI = 25-30%) and 38 cm (*c.*1700-1750 AD; LOI = 55%). Following a relatively minor, short erosion episode between *c.*950-1050 AD (75-

Figure 6.3: Summary diagram of loss-on-ignition profiles from the seven UK and Irish sites studied.



68 cm) LOI values in Blue Lough remained relatively constant suggesting a degree of stability in the catchment until 45 cm (*c.*1400 AD) when sustained erosional activity began in the catchment. Between 45-39 cm (*c.*1400-1500 AD) LOI values increased from 25-55% and erosion intensified during a second phase with an increase in LOI values from 50-80 % between 31-25 cm (c.1600-1700 AD).

A feature common to all of the LOI profiles is the decline in % LOI values within the upper few cm (*c.*1850-1950 AD) of the sediment records. This marked fall in LOI suggests recent widespread stabilisation of catchment peats.

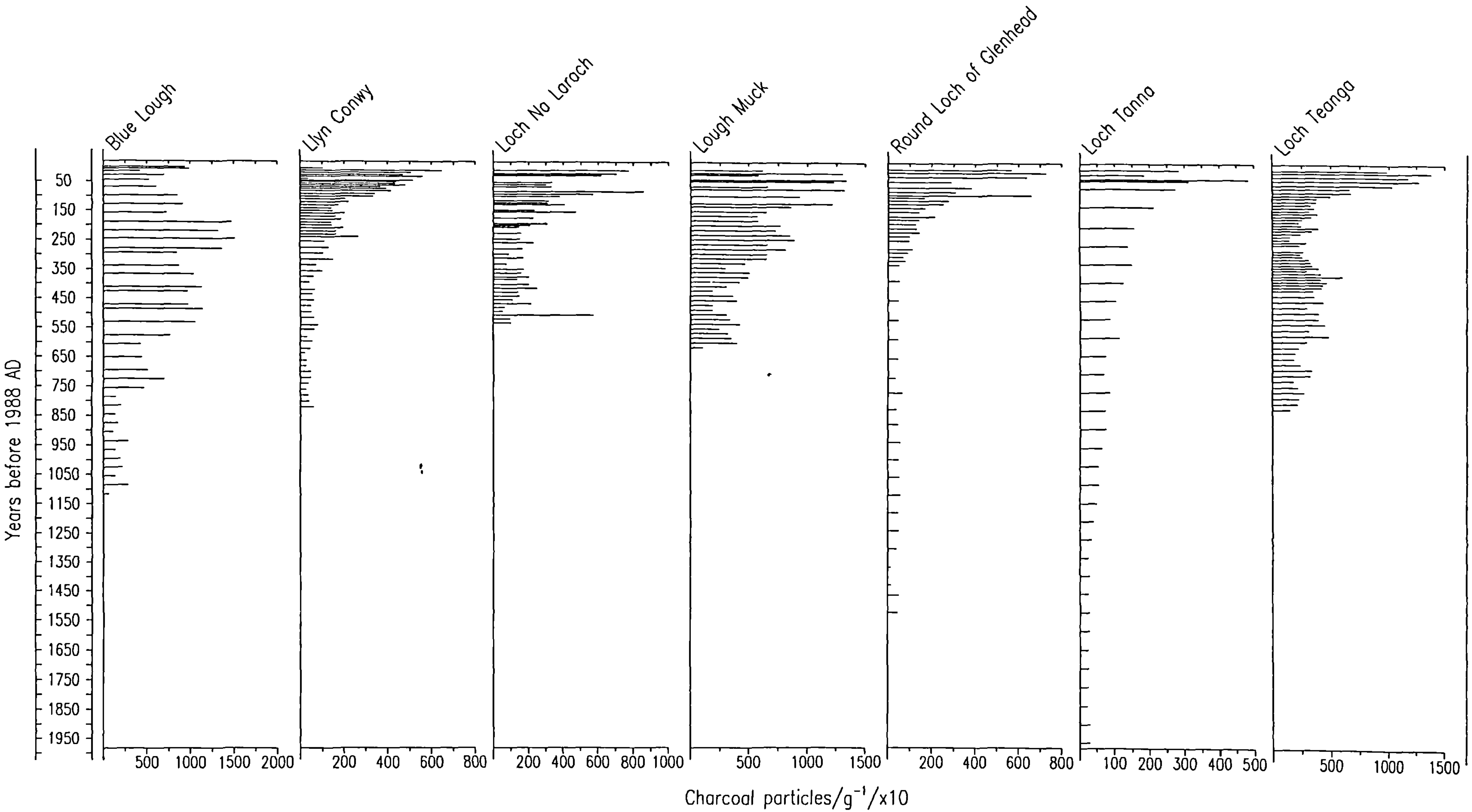
### 6.3.2 Charcoal profiles

The charcoal profiles for the seven cores are presented collectively in Figure 6.4. In this diagram charcoal abundance is taken as an approximate measure of fire activity in the immediate lake catchment as the majority of microscopic charcoal produced by moorland fires is believed to be deposited within a hundred metres of parent fires. Although it is accepted that a small proportion of the charcoal produced may be dispersed extra-locally or even regionally (Clark, 1988a), the overwhelming proportion of charcoal in the lake sediment cores sampled is hypothesised to have local origins (Sugita, 1993, 1994) (see Section 2.3.3).

In the Blue Lough sediment core charcoal levels remain relatively low below 56 cm (*c.*1200-1250 AD) before catchment burning levels increased gradually through to 38 cm (*c.*1500 AD). The period between 35-18 cm (*c.*1500-1800 AD) has sustained high charcoal abundance suggesting it was the period of greatest fire activity in the catchment. Over the past century burning activity fell, although in the last decade fire activity increased again. At Llyn Conwy prior to 57 cm (*c.*1750 AD) charcoal values are low and fairly constant denoting relatively low levels of catchment burning activity. A period of moderate intensification of burning activity prevailed between 57-29 cm (*c.*1750-1900 AD), and post-1900 fire activity (above *c.*29 cm) in the catchment intensified further.

With the exception of a large peak in charcoal abundance at 76 cm (*c.*1480 AD) fire activity in the Loch Na Larach catchment prior to *c.*1800-1850 AD was considerably less intensive than during more recent times. In the Lough Muck catchment fire activity

Figure 6.4: Summary diagram of microscopic charcoal profiles from the seven UK and Irish sites studied.



has been significantly greater in the last couple of centuries (above *c*.22 cm) than previously, although the period between 47-30 cm (*c*.1650-1800 AD) also experienced increased levels of burning compared with the preceding three centuries. The Round Loch catchment experienced consistently low levels of fire activity between 90-45 cm (*c*.400-1700 AD), between 45-28 cm (*c*.1700-1800 AD) charcoal levels were marginally but consistently higher, and in the post-1800 AD period charcoal levels have been much higher suggesting an increase of fire activity in the catchment.

The Loch Tanna charcoal record is similar to that from the Round Loch, high charcoal values during the past hundred years (above *c*.7 cm) suggest a high intensity of fire management, whilst fire activity was relatively low prior to this time, with fire activity increasing only gradually through the 14th and 15th centuries. The Loch Teanga charcoal profile exhibits the familiar (present in all but Blue Lough) period of intensive fire activity in the post-1900 period (above 14 cm), prior to *c*.1900 AD fire activity in the catchment was less intensive.

### 6.3.3 Results of the statistical analyses

The results of the redundancy analyses of the biostratigraphical data sets at the seven sites are presented in Table 6.1 as exact Monte Carlo significance values (499 permutations) (Korsmann *et al.*, 1994).

Blue Lough is the only site at which there is a highly significant relationship between the charcoal record of catchment fire activity and the LOI record of erosion as assessed by restricted Monte Carlo permutation tests. At the other six sites no significant relationship between the charcoal and LOI profiles is shown (p-values = 0.176 - 0.908). The amount of variance in the LOI data explained by the first canononical axis from the RDA analyses at the six sites varied greatly. At Blue Lough 59% of the variance was explained whilst for those sites with no significant relationships between charcoal and LOI much less variance was explained (0 - 38%).

Table 6.1: Results of the redundancy analyses and Monte Carlo permutation tests to determine the effect of catchment fire activity on peat erosion. Entries are percentages of variance explained by the first canononical axis and significance levels as assessed by restricted Monte Carlo permutation tests (499 permutations).

| Site | Predictor | % variance in LOI explained by first RDA-axis | Significance of explained variance (p-value) |
|---|---|---|---|
| Blue Lough | Charcoal | 59 | 0.002 |
| Lough Muck | Charcoal | 38 | 0.176 |
| Llyn Conwy | Charcoal | 11 | 0.604 |
| Loch Na Larach | Charcoal | 3 | 0.820 |
| Round Loch of Glenhead | Charcoal | 15 | 0.480 |
| Loch Tanna | Charcoal | 17 | 0.348 |
| Loch Teanga | Charcoal | 0 | 0.908 |

## 6.4 Discussion

### 6.4.1 Dates of erosion inception

The approximate dates of erosion inception span between *c*.950 AD at Loch Tanna through to *c*.1800 AD for the latest episode of erosion at Loch Teanga, Figure 6.3 & Table 6.2.

Table 6.2: Dates of erosion inception in the seven UK and Irish sites studied.

| Site | Date of erosion inception (AD) |
|---|---|
| Loch Tanna | 900 |
| Llyn Conwy | 1340 |
| Blue Lough | 1380 |
| Loch Teanga | 1530 |
| Lough Muck | 1550 |
| Loch Na Larach | 1560 |
| Blue Lough | 1610 |
| Loch Na Larach | 1640 |
| Llyn Conwy | 1660 |
| Round Loch of Glenhead | 1660 |
| Loch Teanga | 1690 |
| Loch Teanga | 1800 |

The majority of erosion across the range of sites is concentrated within the 16th and 17th centuries, the possible reasons for this are discussed in depth in Section 6.4.2.4. In order to establish how the dates of erosion inception at the seven sites fitted into the framework found in previous studies the dates of erosion have been compared with those from other studies in Table 6.3.

Table 6.3: Approximate dates of erosion inception for selected British and Irish sites. All sites included have been dated by radiometric methods. The sites are listed by country and in chronological order of erosion inception within each country.

| *Site* | *Approximate date of erosion inception (Years AD unless stated)* | *Author* |
|---|---|---|
| **Ireland** | | |
| Arts Lough (Co. Wicklow) | 1000 BC | Bradshaw & McGee (1988) |
| Slieveanorra Forest (Co. Antrim) | 150 BC | McGreal and Larmour (1979) |
| Lough Nabrackbaddy (Co. Donegal) | 450 | Bradshaw & McGee (1988) |
| *Blue Lough (N Ireland)* | *1380* | *This study* |
| Lough Maam (N Ireland) | 1501 | Stevenson (1992) |
| *Lough Muck (Co. Donegal)* | *1550* | *This study* |
| *Blue Lough (N Ireland)* | *1610* | *This study* |
| Lough Maam (N Ireland) | 1776 | Stevenson (1992) |
| Wicklow Mountains | 1850 | Bowler & Bradshaw (1985) |
| **Scotland** | | |
| Lochan Dubh (NW Scotland) | 871 | Stevenson (1992) |
| *Loch Tanna (Arran)* | *900* | *This study* |
| Lochan Dubh (NW Scotland) | 1391 | Stevenson (1992) |
| Glen Etive (NW Scotland) | 1400 | Brazier *et al.* (1988) |
| Glen Feshie (N Scotland) | 1500 | Brazier & Ballantyne (1989) |
| *Loch Teanga (S Uist)* | *1530* | *This study* |
| *Loch Na Larach (N Scotland)* | *1560* | *This study* |
| Loch Laidon (NW Scotland) | 1568 | Stevenson (1992) |
| *Loch Na Larach (N Scotland)* | *1640* | *This study* |
| *Round Loch of Glenhead (SW Scotland)* | *1660* | *This study* |
| *Loch Teanga (S Uist)* | *1690* | *This study* |
| Several sites in the Scottish Highlands | 1730 | Innes (1983) |
| *Loch Teanga (S Uist)* | *1800* | *This study* |
| Lochan Dubh (NW Scotland) | 1809 | Stevenson (1992) |
| Loch Chon (NW Scotland) | 1826 | Stevenson (1992) |
| **England** | | |
| Howgill Fells (NW England) | 1000 | Harvey *et al.* (1981) |
| Featherbed Moss (N England) | 1770 | Tallis (1985) |
| **Wales** | | |
| *Llyn Conwy (N Wales)* | *1340* | *This study* |
| *Llyn Conwy (N Wales)* | *1660* | *This study* |
| Llyn Peris (N Wales) | 1750 | Dearing *et al.* (1981) |

NB - It is acknowledged that the above list of sites is by no means comprehensive, however, it serves the intended purpose of placing the study sites in a wider spatial and temporal framework. Large numbers of additional sites were not used because it was deemed that their methods of dating were questionable.

The majority of the erosion episodes listed above, 18 of the 26, were initiated between *c.*1500-1850 AD. This broadly synchronous timing of erosion inception over such a wide geographical range of sites is extremely interesting and is addressed fully in Section 6.4.2.4.

### 6.4.2 The possible causes of erosion

#### 6.4.2.1 Fire activity

Fire has been implicated in a considerable number of palaeoenvironmental studies seeking to determine the causes of peat erosion, although often with little direct evidence (*e.g.* Stevenson & Thompson, 1993; Innes, 1983a, 1983b; Brazier *et al.*, 1988). The main reason for this may be that fire has such great potential for causing erosion. The susceptibility of upland peats to erosion being greatly enhanced by the removal of the protective vegetation cover, and fires, particularly uncontrolled high temperature/intensity ones, can initiate prolonged erosional events (*e.g.* Radley, 1962; Tallis, 1964; Maltby *et al.*, 1990).

The underlying assumption of the methodology adopted here is that increased fire activity in a catchment, inferred from increased quantities of microscopic charcoal in the lake sediments, increases the likelihood of erosion of catchment peats. Whilst it is accepted that there is not necessarily always a positive and causal relationship between high levels of fire activity and erosion, *i.e.* moors managed by intensive, controlled muirburn can be free of serious and prolonged erosion (Gimingham, 1972), areas of blanket peat devoid of vegetation following fires are potentially more susceptible to erosion than unburned areas (Imeson, 1971; Kinako & Gimingham, 1980). Therefore, it is not unreasonable to hypothesise that the 'erosion potential' of a catchment may be related to the degree of fire activity within it.

The palaeoenvironmental and statistical analyses conducted were designed to assess the extent to which catchment fire activity may have been responsible for initiating the past erosion of peats in the seven catchments studied (Figures 6.5 - 6.11). Redundancy analysis (RDA) and Monte Carlo permutation tests, offer a robust means of determining

Figure 6.5: Loss-on-ignition and microscopic charcoal profiles for Blue Lough.

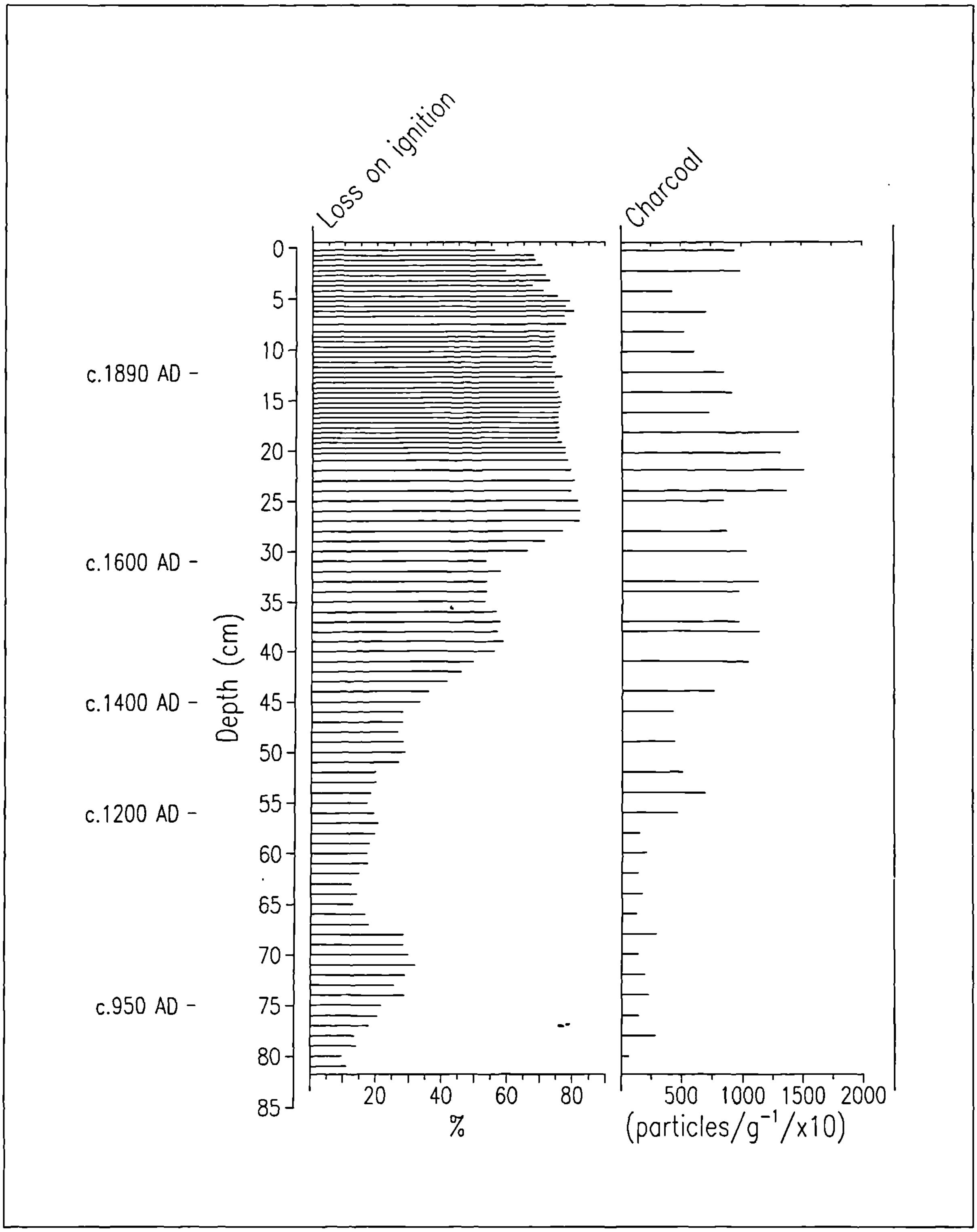


Figure 6.6: Loss-on-ignition and microscopic charcoal profiles for Llyn Conwy.

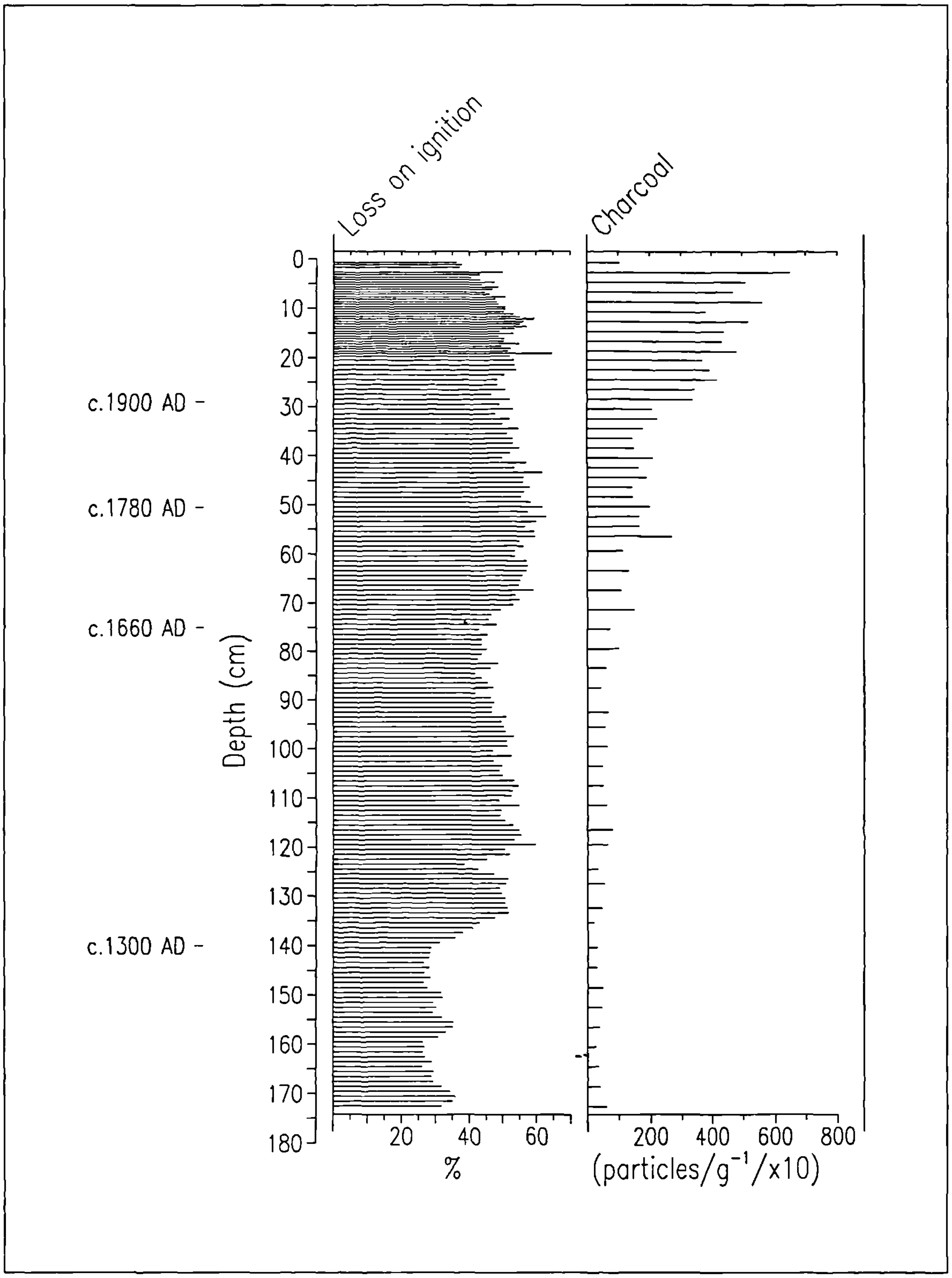


Figure 6.7: Loss-on-ignition and microscopic charcoal profiles for Loch Na Larach.

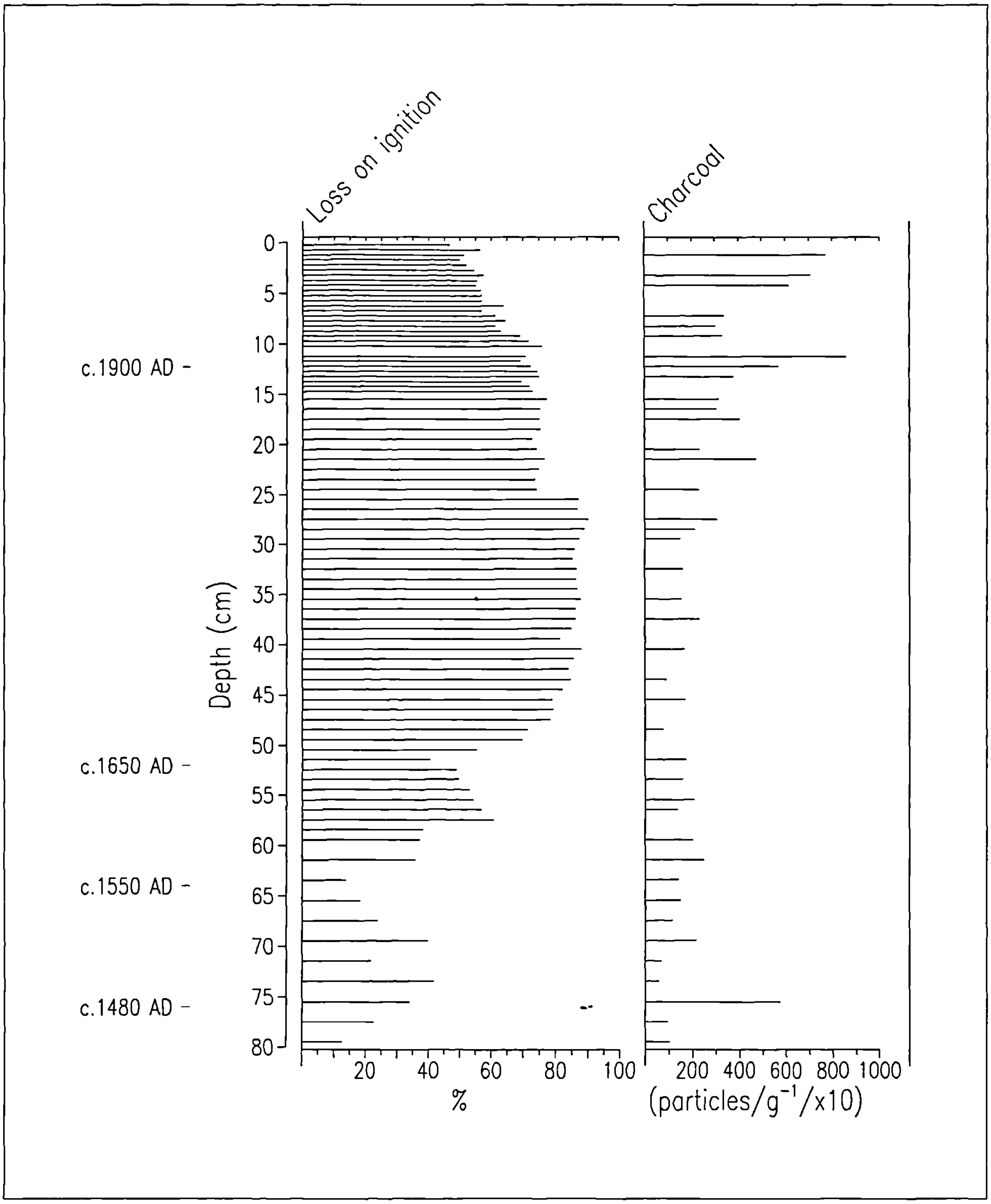


Figure 6.8: Loss-on-ignition and microscopic charcoal profiles for Lough Muck.

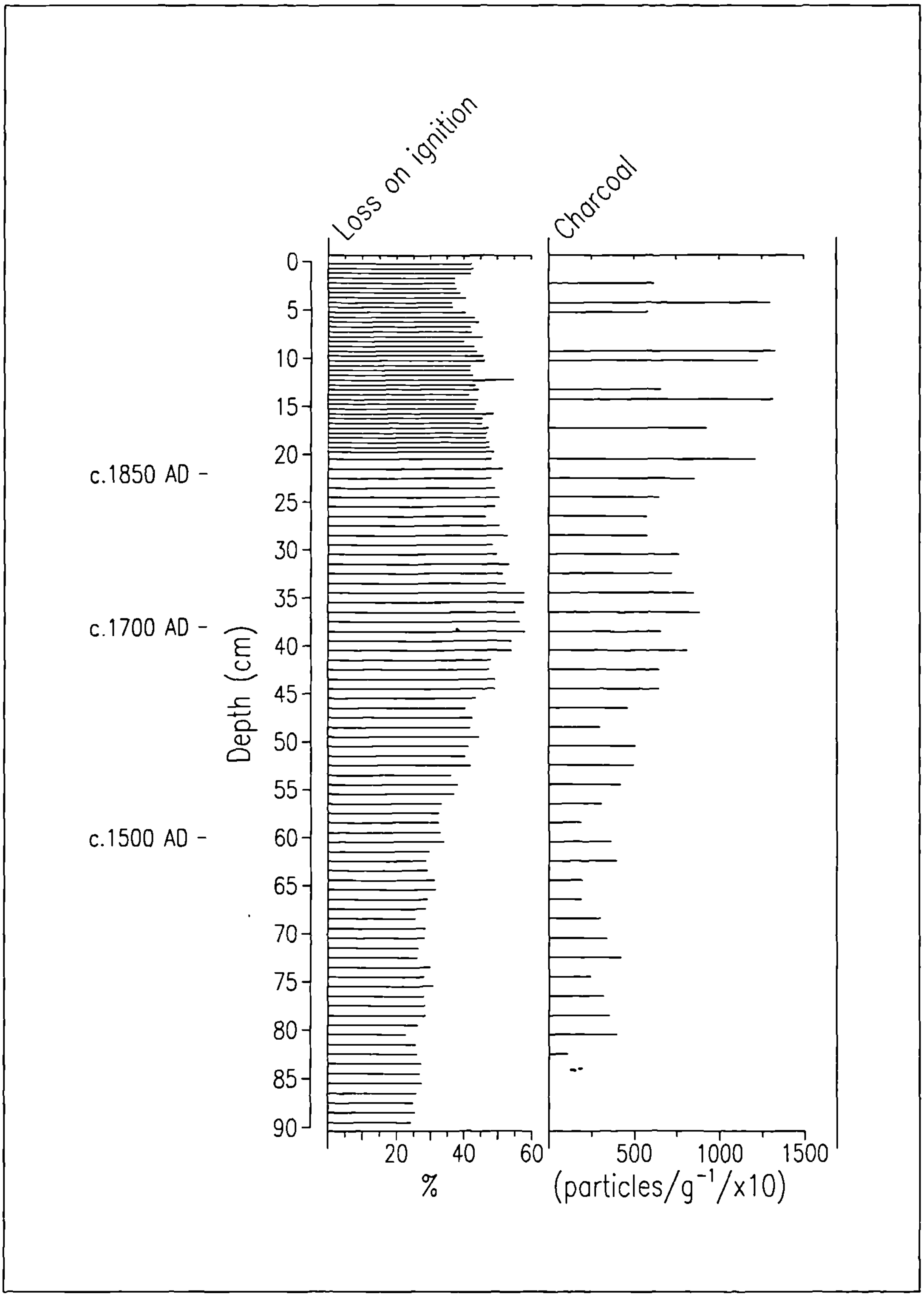


Figure 6.9: Loss-on-ignition and microscopic charcoal profiles for Round Loch of Glenhead.

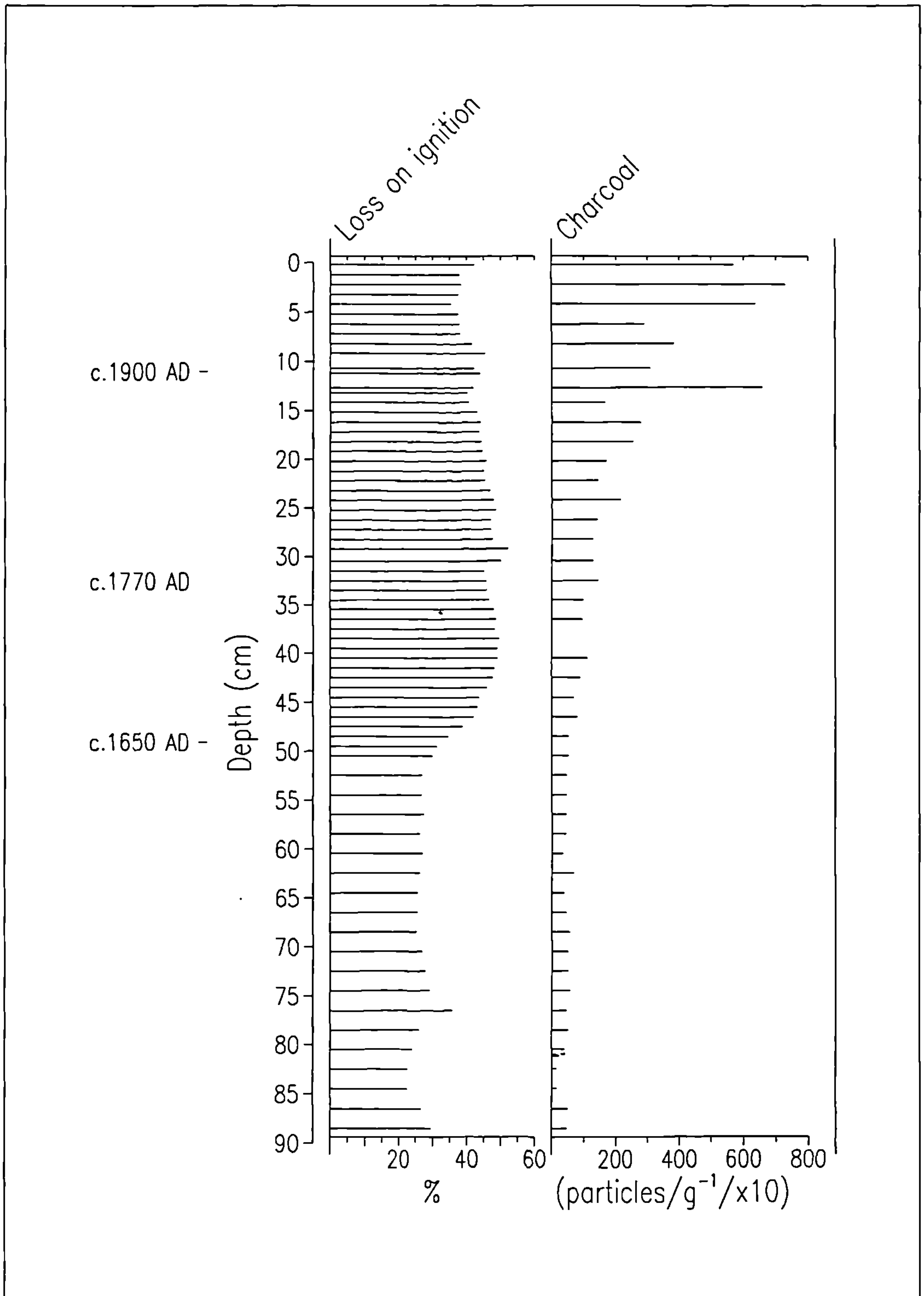


Figure 6.10: Loss-on-ignition and microscopic charcoal profiles for Loch Tanna.

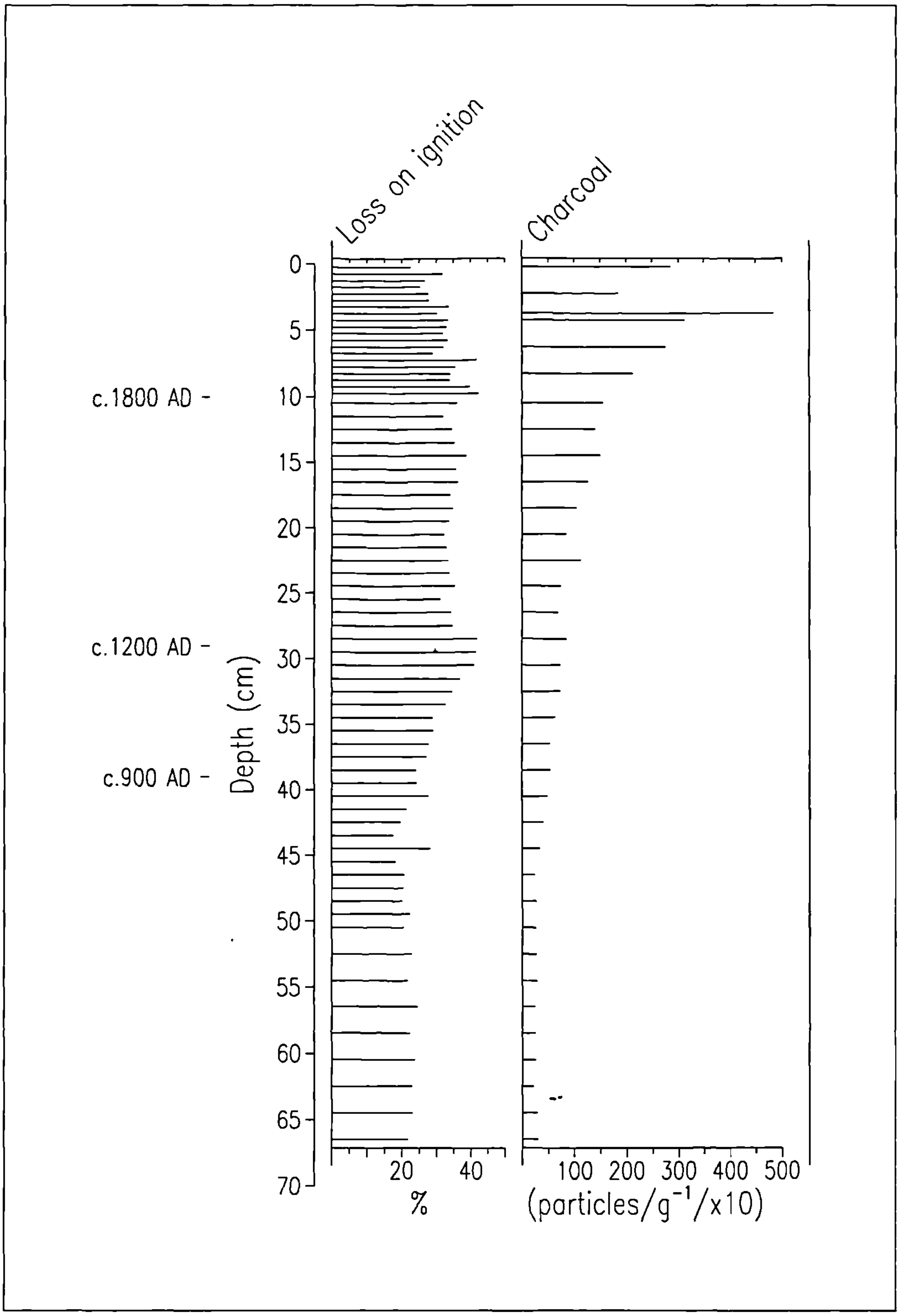
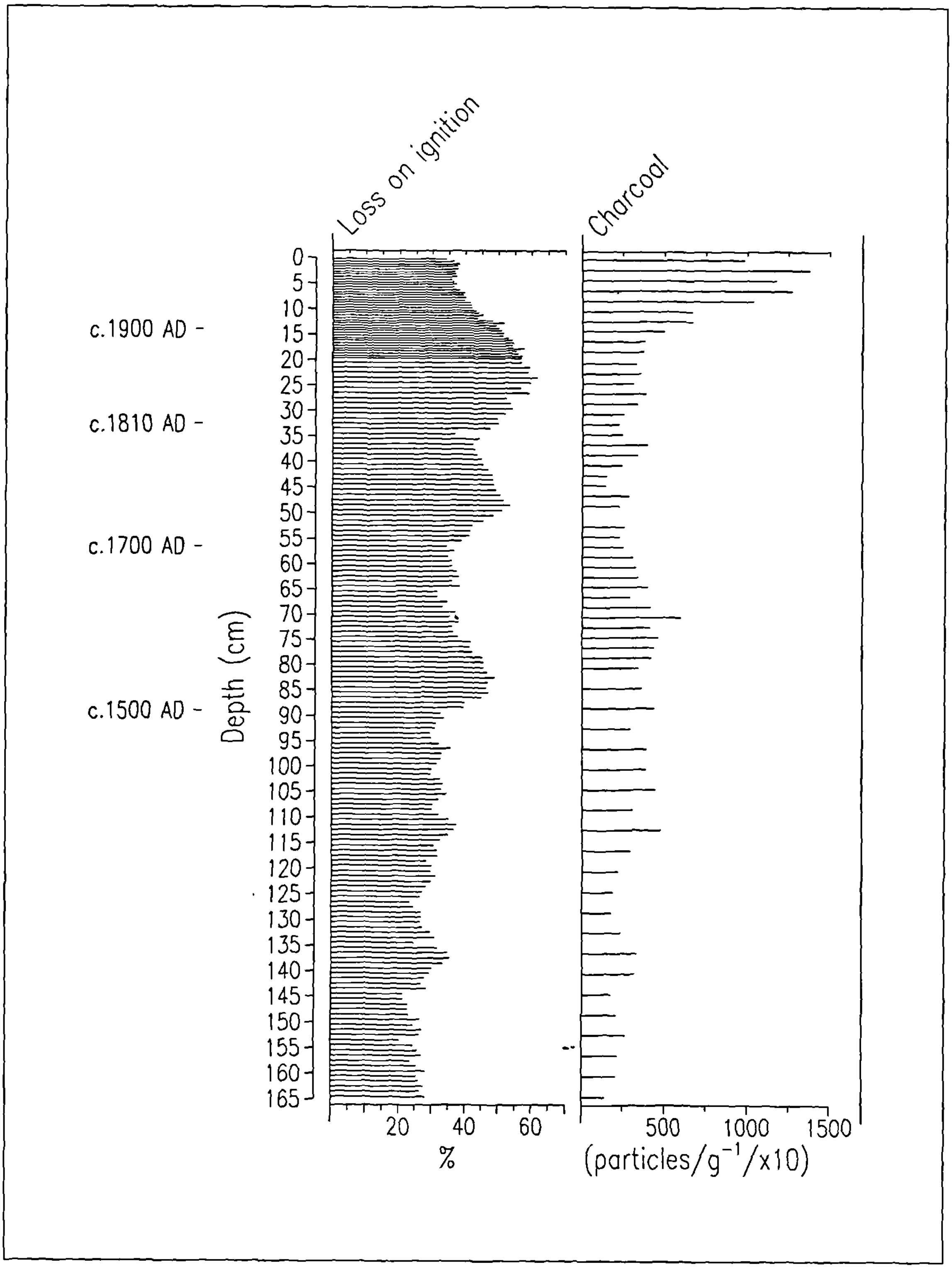


Figure 6.11: Loss-on-ignition and microscopic charcoal profiles for Loch Teanga.



the amount of variation in the erosion record attributable to fire activity and its statistical significance (Lotter & Birks, 1993; Korsman *et al.*, 1994).

The results of the analyses, presented in Table 6.1, indicate that at only one of the seven sites, Blue Lough, was there a highly significant relationship ($p = 0.002$) between catchment erosion (LOI) and changing catchment burning regime as assessed by restricted Monte Carlo permutation tests. The analyses suggest that at Blue Lough intensification of fire activity may have been an important factor contributing to the initiation of erosional events. These results, however, do not prove that fire activity was solely responsible for causing erosion, they do, however, provide evidence for evaluating whether it may have had a contributory role. The roles of all the other possible causes of peat erosion also need to be assessed before the most important factors could be determined.

At the other six sites catchment burning was not found to be a statistically significant factor causing or contributing toward erosion inception. The p-values assessed by Monte Carlo permutation tests are not significant and the percentages of variance in the LOI profiles explained by the charcoal variable are low. With the exception Lough Muck (38%) very little of the variance (<17%) was explained by the charcoal variable for these six sites and in the most extreme case, Loch Teanga, none of the variance in the LOI profile was accounted for by the charcoal index.

In summary, the analyses presented here illustrate that whilst in the case of Blue Lough burning of catchment vegetation may have been instrumental in causing erosion, at the other sites despite their long histories of fire management, alternative agents and processes may have been responsible for initiating erosion. The alternative hypothesised causes of erosion are discussed below.

#### 6.4.2.2 Atmospheric pollution

Atmospheric pollutants, especially sulphur-derived compounds from the combustion of fossil fuels can adversely affect or even cause the death of *Sphagnum* spp. and lichens (Ferguson *et al.*, 1978; Ferguson & Lee, 1979). Tallis (1964) and Chambers *et al.* (1979) believe that atmospheric contaminants have been a possible cause of, or at least an important contributory factor in the perpetuation of, peat erosion in the Pennines and

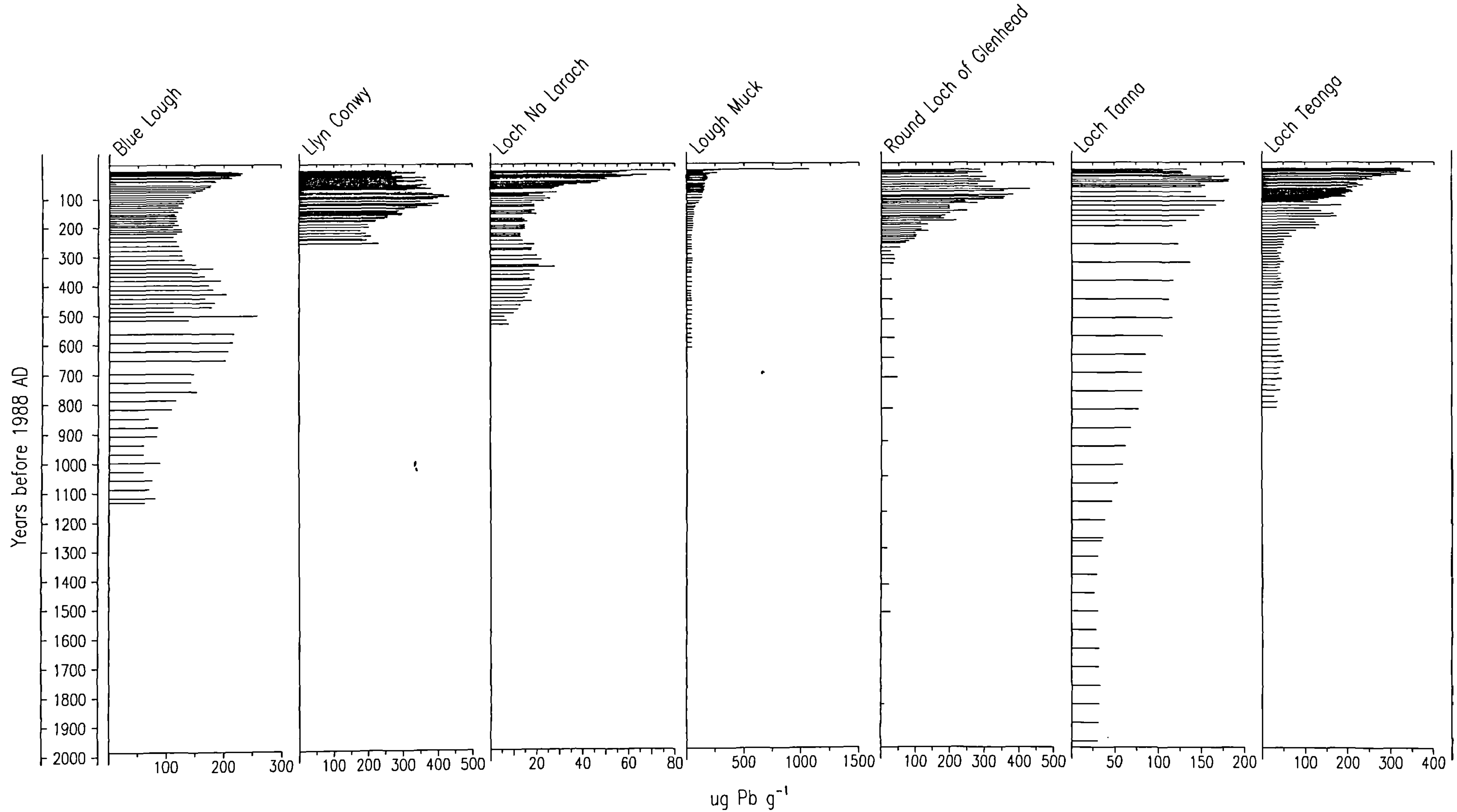
N. Wales. The demise of Sphagna and a subsequent lack of recolonisation of exposed peat surfaces increases the chances of severe erosion occurring and prolongs its deleterious effects.

Sulphur compounds have been measured directly in palaeolimnological studies to provide a direct measure of past atmospheric contamination and acid stress on catchments (*e.g.* Nriagu & Coker, 1983; Holdren *et al.*, 1984; Mitchell *et al.*, 1985). However, sulphur sedimentation processes are prone to changes in efficiency as lake conditions change and sediment records do not always record sulphur input histories accurately (Nriagu & Soon, 1985; Rudd *et al.*, 1986; Rippey, 1990). To overcome this problem alternative strategies have been developed. The trace metal Pb has a depositional history approximately similar to acidic contaminants and because it is less susceptible to mobilisation in lacustrine sediments can be used as surrogate measure of the deposition of atmospheric acidity (Galloway & Likens, 1979; Norton *et al.*, 1981; Wong *et al.*, 1984; Battarbee *et al.*, 1985). Pb is so stable in all but the most acidic environments that it is customary in studies of this nature to interpret lead profiles in terms of anthropogenic effects and to ignore or exclude the possibility of a diagenetic contribution (Kemp & Thomas, 1976).

A large number of studies have illustrated that most lakes in Britain and Ireland exhibit generally similar histories of pollutant deposition. Lacustrine sedimentary pollutant levels generally remain low throughout the lower profile until *c.*1800-1850 AD when they increase markedly up profile, the result of industrial expansion during this period (*e.g.* Farmer *et al.*, 1980; Rippey *et al.*, 1982; Jones *et al.*, 1990; Rippey, 1990; Williams, 1991).

The Pb profiles at five of the seven sites analysed (Figure 6.12), Llyn Conwy, Loch Na Larach, Lough Muck Round Loch and Loch Teanga, conform to that which might be expected. Generally low and constant levels of Pb show marked enrichment in the upper profiles post-1800 to 1850 AD. In contrast the Blue Lough and Loch Tanna profiles exhibit considerable enrichment further down their profiles. In both instances changes in the sediment constitution were responsible for the pre-industrial enrichment of the sediments, due to increased influxes of mineral-rich, finer sediments with associated

Figure 6.12: Summary diagram of lead profiles from the seven UK and Irish sites studied.



higher trace metal burdens from the catchment. The increased lead deposition in the lake is therefore the result of geomorphic processes in the catchment rather than atmospheric deposition, and is a consequence of erosion rather than a cause of it (Patrick *et al.*, 1989; Flower *et al.*, 1990). The two sites still, however, exhibit the characteristic increases in Pb concentration in their upper sediments as a result of industrially derived atmospheric contamination

The concentrations of Pb in the cores vary considerably, both in terms of background levels which are the consequence of local geology, and industrial contamination which is primarily dependent upon proximity to industrial activity (Farmer *et al.*, 1980). Peak concentrations in the surficial sediment range between 1068 ug/g in Lough Muck, an uncharacteristically high value in the context of the rest of the core, to only 78 ug/g in Loch Na Larach. Loch Na Larach is considerably further from industrial enterprises than Lough Muck. A feature common to most of the Pb profiles is a general reduction in pollution levels in the past few decades, this is perhaps due to reduced industrial emissions at source as a result of increased pollution controls (Williams, 1991).

Acid deposition can be rejected as an important cause of past erosion initiation in the seven catchments studied because the increases in pollutant deposition experienced at these sites occurred considerably later than erosion had been initiated, similar conclusions were reached by Bradshaw & McGee (1988) and Stevenson *et al.* (1990; 1992). In addition, the sites have not been subjected to high enough levels of pollution to cause severe *Sphagnum* damage. Studies in which atmospheric pollution has been implicated as a significant cause of *Sphagnum* spp. loss and damage have been confined to the Peak District where because of the proximity to major industrial centres the effects were most severe (Ferguson & Lee, 1983).

**6.4.2.3 Grazing**

Studies of sheep grazing on moorland and blanket bog vegetation have highlighted the importance of grazing in modifying vegetation (*e.g.* Hunter, 1962; Welch & Rawes, 1966; Rawes & Williams, 1973; Grant *et al.*, 1976; Hewson, 1977; Welch, 1984; Rawes

& Hobbs, 1979). Blanket bog is particularly vulnerable to overgrazing, especially in combination with periodic burning (McVean & Lockie, 1969). Rawes (1983), for instance, studied changes in the high altitude blanket bog vegetation on Moor House Nature Reserve and concluded that the role of grazing animals in determining vegetation community cover and structure has long been underestimated, 'climate had previously been considered the main factor controlling the vegetation but the importance of sheep grazing soon became apparent.'

Heavy grazing preferentially favours the expansion of graminoid species over *Callunetum*, and tussock-forming graminoids offer less complete ground cover and, therefore, less protection from erosion (Eddy *et al.*, 1969; Evans, 1977; Phillips *et al.*, 1981). Grazing is also influential in prolonging phases of erosion by preventing vegetation regeneration on bare ground, an extremely important factor necessary for arresting erosive processes. Sheep preferentially graze the short nutritious vegetation developing on recently burned areas and grassy areas in heather dominated communities and increase their potential for erosion (Grant *et al.*, 1976).

Sheep hooves are sharp-edged and exert more than twice as much pressure on the ground than human feet (Phillips *et al.*, 1981), well trodden tracks and paths along contours greatly increase the instability of hill slopes (Shimwell, 1974; Fairbairn, 1963). 'Sheep scars' are also a common feature of eroded hill slopes in areas of high stocking levels (Fairbairn, 1963; Bower, 1961). Initiated as small tears behind irregularities where sheep shelter from the weather, these initially insignificant disturbances become wider and deeper as the soil surface is exposed to the elements and further disturbance by sheep. Ballantyne (1986, 1987) and Ballantyne & Whittington (1987) also attribute some of the blame for accelerated wind erosion and mass movements on some mountain summits to disturbance by sheep.

A considerable number of studies have implicated sheep grazing in the initiation of specific historic erosion events. The implication of sheep grazing as an agent of erosion in palaeoenvironmental studies, however, has in most cases been rather 'speculative' and has tended to rely on rather vague coincidences in timing between possible human occupation, with assumed livestock farming, and erosional events (*e.g.* Bennett *et al.*, 1990; Harvey *et* *al.*, 1981; Dearing *et al.*, 1981). In practice the effects of past grazing are extremely difficult to estimate using palaeoecological data as there is no direct fossil evidence in sedimentary sequences. Effects on vegetation communities manifested in the pollen spectra may be determinable under very high resolution examination, but even then it is very difficult to differentiate the effects due solely to grazing from those of other factors such as climate, pollution and burning which are superimposed, often imperceptibly, on the pollen record.

Modern studies into the effects of variations in stocking levels on *Calluna*-dominated upland vegetation have provided guidelines to the approximate sheep densities which can be sustained before the vegetation is deleteriously affected. Stocking levels under which *Callunetum* has been found not to be detrimentally affected are as follows: <0.62 ewes/ha on areas grazed throughout the year (Jones, 1964); 0.83 ewes/ha with intense shepherding and grouse management (Wilson, 1979); and 2.18 sheep/ha on heather moor under summer grazing only (Hewson, 1977). Alternatively, stocking levels at which deleterious effects have been experienced include the following: under 3.28 sheep/ha heather was almost completely suppressed (Hewson, 1977); grazing of 0.5 sheep/ha on burnt blanket bog suppress heather (Rawes, 1971); and Evans (1977) at Hey Clough calculated sheep densities of 1.71-1.89 sheep/ha cause the appearance of bare ground and, therefore, initiate erosion.

Phillips *et al.* (1981) warn that such generalised stocking levels must be interpreted with great caution because heather growing on sub-optimal sites, such as a poorly-drained or base-rich ones, stands less pressure than plants growing on well-drained peats. Grant & Hunter (1968) and Sydes & Miller (1988) also stress that stocking rates are a crude and imperfect, if not meaningless, guide to the likely grazing pressures experienced by a particular area as they make no allowance for diurnal and seasonal changes in herbivore distribution, or account of local concentrations of livestock on small areas of good or sheltered grazing. However, no other guide to grazing pressure is often available (Sydes & Miller, 1988).

Past stocking densities and their possible impacts in terms of erosion are extremely difficult to reconstruct over limited, never mind extended, time scales. Approximate grazing intensities can be determined using historical documentary evidence, but even when records are good it is very difficult to ascertain exact stocking levels for catchments which can prove constructive for detailed analysis. The longest and most accurate grazing histories are perhaps those that have been derived for areas which were under the control of Cistercian Monasteries since Mediaeval times. Hughes *et al.* (1973) were able to reconstruct an excellent grazing intensity record for an area of North Wales under Cistercian control from *c.*1300 AD. In *c.*1300 AD stocking levels of sheep were only on average *c.*0.12 sheep $ha^{-1}$, levels rose progressively through to *c.*1600 to a level of *c.*0.5 sheep $ha^{-1}$, then sheep populations subsequently rose more dramatically and in 1700 AD they were c.1.73 sheep $ha^{-1}$, around 1800 = c.3 sheep $ha^{-1}$, and in 1877 = 3.95 sheep $ha^{-1}$, however, during the early 20th century levels fell to *c.*0.9 sheep $ha^{-1}$ in 1920 but rose again to 2.96 sheep $ha^{-1}$ by 1969. Although the stocking record is as good as could possibly be reconstructed the authors warn against using the figures in detailed analyses because they represent a series of approximations, derived from extant historical facts, and 'cannot be regarded as satisfactory for statistical inference' (Hughes *et al.*, 1973).

Sheep have been the main, and in many areas the only, grazing animals in the uplands of Scotland since the late 18th century (Hobbs & Gimingham, 1987; Ritchie, 1919, 1920). Prior to that, under the shieling management regime, cattle were predominant on the remote and rough grazings during summer only along with some goats and sheep (Ritchie, 1919, 1920; Sydes & Miller, 1988). The introduction of commercial sheep farming breeds, especially the Blackface and the Cheviot, and year-round grazing occurred shortly after the 1745 revolution and effectively ended the use of the shieling system (Fenton, 1980; Innes, 1983). Watson (1932) highlights the extent of the expansion in sheep densities in some areas around this time, *e.g.* in an area near Callendar in 1770 1,000 sheep were grazed but over the next 20 years the number increased to 18,000. By 1830 the transition to commercial sheep farming was complete over most of Scotland, however, between 1850-1880 sheep farming in some regions declined and deer farming increased due to demand for sporting estates (Innes, 1983). Sheep farming expanded again at the beginning of World War 1 and has continued through to the present day, with the Highlands experiencing 3-4 fold increases in stocking densities over the past 50 years

(Sydes & Miller, 1988; Patrick & Stevenson, 1990; Thompson *et al.*, 1993). Hobbs & Gimingham (1987) estimate that current stocking rates of hill sheep in Scotland are generally in the range 1.2-2.8 sheep/ha.

Commercial sheep farming in Scotland since the late 19th century has frequently been blamed for the degradation of the landscape. Darling (1968) believed that 'two centuries of extractive sheep farming ....... have reduced a rich resource to a state of desolation', and whilst Mather (1994) takes a more tempered view he concludes that 'there is little doubt that the Highland environment has been significantly modified by sheep farming over the last two hundred years', however in his mind 'there is much more doubt about the nature, pattern and magnitude of that modification'.

In comparison with England, Scotland and Wales relatively little is known about long-term grazing patterns and intensities in Ireland, although it is believed that sheep grazing intensities in the majority of Irish catchments generally remained much lower than in the UK throughout the last 200 years. Sheep populations only expanded significantly in the mid 1960s and 1970s (O'Toole, 1985).

Has excessive grazing pressure been responsible for the initiation of peat erosion in the catchments studied? In the Loch Tanna catchment the inception of erosion occurred *c.*900-1000 AD, and although Harvey *et al.* (1981) invoked grazing pressures attributable to Norse settlers during a similar period in the Howgill Fells, it is felt that it is unlikely that grazing pressures at this time could have been solely responsible for initiating erosion in this catchment. Round Loch of Glenhead, located in Galloway, SW Scotland may have fallen within the ranges of early Cistercian pastures, however, even if it did the sheep and cattle populations *c.*1600 AD are unlikely to have caused major catchment erosion on the scale recorded. The other Scottish sites in more remote locations are unlikely to have been subjected to excessively severe grazing regimes prior to the establishment of commercial sheep farming toward the end of the 18th century. Initial phases of erosion in these catchments all pre-date the onset of commercial sheep farming by considerable margins, grazing can thus be rejected with a high degree of confidence as the likely cause. In Ireland erosion in the catchments of Lough Muck and Blue Lough is inferred to have begun in the 14th and 16th centuries respectively, well before grazing intensities are likely to have been sufficiently high to have caused erosion. The Llyn Conwy catchment lies very close to the boundaries of the grazing ranges of the Cistercian monasteries in N Wales studied by Hughes *et al.* (1973). However, with the initial phase of erosion at the site occurring in the 14th century, before significant expansions in sheep populations, it is unlikely that grazing played an important role in erosion inception.

It can be concluded, therefore, that sheep grazing is unlikely to have been the principal agent responsible for the initiation of peat erosion in the catchments studied. However, grazing may have played a significant role in exacerbating and perpetuating erosion in more recent times, following its inception in at least some of the catchments studied.

#### 6.4.2.4 Climate change

Climate is considered to exert a fundamental control on peat erosion (Bower, 1959, 1961, 1962; Moss, 1913; Conway, 1954; Johnson 1957). Not only are the main agents of erosion climatic, *i.e.* intense precipitation, wind, frost action and desiccation, but the prevailing climate dictate rates and characteristics of peat development, and the general vegetation cover. It is, therefore, understandable that when past erosion episodes have been coincidental with periods of known climatic severity, climatic factors have been invoked as possible causes (*e.g.* Conway, 1954; Tallis, 1965, 1973; McVean & Lockie, 1969; Tomlinson, 1982). The Little Ice Age, characterised by increased climatic severity and storminess (Lamb, 1977, 1982; Grove, 1988), in particular has been widely associated with erosional activity (*e.g.* Brazier & Ballantyne, 1989; Stevenson *et al.*, 1990).

Nine of the twelve major erosion episodes experienced by the catchments studied were initiated between *c.*1530-1800 AD with five of the seven sites studied, Llyn Conwy in N Wales, Round Loch of Glenhead in SW Scotland,-Lochs Na Larach and Teanga in NW Scotland, and Blue Lough in N Ireland, experiencing distinct episodes of erosion between *c.*1600-1700 AD. The high degree of conformity in timing between erosion events across such a spatially spread range of sites suggests that climate, rather an anthropogenically induced cause (*i.e.* pollution, burning or grazing) may have been responsible for erosion initiation especially as the timing of the erosion episodes fall within the approximate temporal boundaries of the Little Ice Age (*c.*1550-1850 AD; Lamb, 1977, 1982). Whilst it is tempting to hypothesise a possible climatic cause for the onset of the erosion at these sites there is, however, no direct indisputable evidence of this in the palaeoecological data available. Ballantyne (1991) warns that such explanations based upon apparent coincidences in timing are difficult to sustain because of the insufficiently precise evidence. The Little Ice Age was characterised by great variability in climatic conditions on both a year-to-year basis and between groups of years from between 6-8 years (Lamb, 1977; 1982), therefore, extremely accurate and well dated palaeoenvironmental data is needed to correlate erosion records with periods of climatic severity and mildness within the wider umbrella of predominantly poor conditions of the Little Ice Age. Unfortunately, sufficiently precise and accurate chronologies are not available for the sites used in this study, and thus the association between the inception of erosion and perceived climatic deterioration is relatively weak.

Ballantyne (1991) also points out that climatic interpretations rely heavily upon the assumption that climatic deterioration is somehow necessarily associated with increased landscape instability. Whilst it is true that all peat masses would not necessarily have been de-stabilised by more severe winters and summers, evidence from contemporary studies of extreme peat erosion episodes suggests that intense rainstorms in both winter and summer are responsible for initiating the majority of modern erosional episodes, therefore, suggesting that periods in the past in which such events were more frequent and severe would have had higher risks of erosion inception (Brazier & Ballantyne, 1989). Indeed, Morgan (1985) concludes that even under the relatively mild current climatic conditions British upland blanket peat environments are unstable and that prolonged storms of low intensity and short-lived intense storms are the most important agents of erosion (Morgan, 1985). It follows, therefore, that during the Little Ice Age, characterised by the coldest climatic regime since the last major ice age and with an increase in the frequency and ferocity of intense cyclonic storms over the North Atlantic exceeding the severity of most of the worst storms of modern times, peatlands are likely to have been more susceptible to erosion. However, it does not prove that they were responsible for the erosional events experienced at the seven sites studied.

Not all of the erosion episodes in the study cores were fell within the approximate extent of the Little Ice Age event. Erosion in the Loch Tanna catchment is estimated to have begun *c.*900 AD, considerably before the Little Ice Age. Can a possible climatic cause be invoked at this site? Lamb (1982) suggests that the 10th century was generally characterised by a remarkable amount of anticyclonic weather over Britain, giving low rainfall, rather warm summers and rather cold winters. A general synopsis which fails to suggest a period of climatic conditions likely to enhance the likelihood of erosion. However, over the past century, although the prevailing climate of Britain and Ireland has not been overly extreme, isolated high intensity storms have cause large numbers of erosional events. It is impossible to ascertain whether erosion at Loch Tanna was caused by climatic events.

Llyn Conwy and Blue Lough both experienced their initial phases of erosion in the 12th century. The 12th century in Europe is believed to have been characterised by general cooling following the period of Mediaeval warmth ('Little Optimum') which spanned from *c.*800-1300 AD (Lamb, 1982). Runs of extraordinary summers, *e.g.* between 1313-1321 AD wet summers, springs and autumns brought crop failure and famine to Britain, and the 1320s, 1330s and 1380s were all very warm, dry and 'droughty' (Lamb, 1982), and there will undoubtedly have been at least several intense storms capable of causing erosion. Again, however, it is impossible to state whether such climatic conditions initiated erosion at the two sites.

As propounded by Ballantyne (1991), therefore, pending further research the present evidence for climatic deterioration being responsible for enhancing erosion is circumstantial and thus any conclusions drawn are to a great degree speculative.

### 6.5 Conclusions

The data and analyses presented fail to fully and unequivocally elucidate the causes of peat erosion at the sites studied. The best estimates of the possible cause of peat erosion episodes at the sites discussed above are, however, summarised in Table 6.4.

Table 6.4: Summary of the possible inferred causes of peat erosion in the seven UK and Irish catchments studied.

| Site | Date of erosion (AD) | Possible causes of erosion inception: Fire? | Little Ice Age? | Pollution? | Grazing? |
|---|---|---|---|---|---|
| Loch Tanna | 900 | No | No | No | No? |
| Llyn Conwy | 1340 | No | No | No | No? |
| Blue Lough | 1380 | Yes? | No | No | No? |
| Loch Teanga | 1530 | No | Yes? | No | No? |
| Lough Muck | 1550 | No | Yes? | No | No? |
| Loch Na Larach | 1560 | No | Yes? | No | No? |
| Blue Lough | 1610 | No | Yes? | No | No? |
| Loch Na Larach | 1640 | No | Yes? | No | No? |
| Llyn Conwy | 1660 | No | Yes? | No | No? |
| Round Loch of Glenhead | 1660 | No | Yes? | No | No? |
| Loch Teanga | 1690 | No | Yes? | No | No? |
| Loch Teanga | 1800 | No | Yes? | No | No? |

NB Entries in this table reflect inferences made from the available information rather than proven facts. They may, therefore, be subject to change and hence the question marks after many of them.

It is clear is that catchment burning has not been solely or significantly responsible for initiating widespread erosion at all of the sites studied. Indeed vegetation burning is only implicated to a statistically significant degree at a single site, Blue Lough. Fire activity within the catchments of the other sites is believed not to have a major role in initiating erosion, however, burning of vegetation cover may have helped to perpetuated and enhanced erosion in these catchments following initial erosion inception by other factors. Further analyses are needed to assess this possible relationship.

The effects of atmospheric pollution have also been dismissed as a major cause of erosion initiation at all of the sites, primarily because all of the erosion events pre-date the nation-wide expansion in industrially derived atmospheric pollution in the mid to late nineteenth century. The possible influence of sulphur and nitrogen pollution at enhancing and prolonging erosion in some areas during recent centuries cannot be ignored (Tallis, 1964; Chambers *et al.*, 1979; Ferguson *et al.*, 1978; Ferguson & Lee, 1979), however, all of the sites used in this study are in locations sufficiently distant from industrial pollution sources for the effects of pollutants to be relatively minimal, or at least not significant enough to cause major vegetation change.

The possible role of grazing as a causative agent of erosion is much more difficult to assess because of a lack of direct evidence in the palaeo-sediment record. It is felt, however, that the predominantly early dates of inception of erosion at most of the sites (*i.e.* pre-1800 AD) discount the likelihood that increased and excessive grazing pressures were responsible for causing vegetation instability and erosion in the catchments. Again, however, because of the important role that sheep play in the perpetuation of erosion in contemporary moorland their influence cannot be wholly and categorically discounted with the present data.

The climatic factors, wind, rain, snow and frost are the primary agents of erosion and the influence of prevailing climatic conditions must be considered a possible key factor in causing erosion (Bower, 1959, 1960, 1961; Hulme & Blyth, 1985; Maltby *et al.*, 1990). Unfortunately, it was not possible within the scope of this project to fully evaluate the possible role of climatic factors as a possible cause of erosion at the sites studied. Inadequacies in the dating control of the cores precluded the satisfactory correlation of the sedimentary LOI records with available decadal-scale climate records (Lamb, 1977). The relationship between climatic change and erosion could not, therefore, be evaluated statistically, in a similar manner to that adopted for the charcoal records. However, the synchronous nature of erosion initiation between the geographically spread sites, and the predominance of erosion inception during the climatically harsh Little Ice Age (c.1500-1850 AD), suggests that extreme climatic conditions may have been an important cause of erosion. Although it is accepted that such evidence is to a degree circumstantial and rather speculative (Ballantyne, 1991), the current data, which tends to preclude the roles of fire, atmospheric pollution and grazing, suggests that climatic influences may have been most important in causing erosion. Obviously, however, further work is needed to validate or disprove these interpretations.

# PAGINATION ERROR

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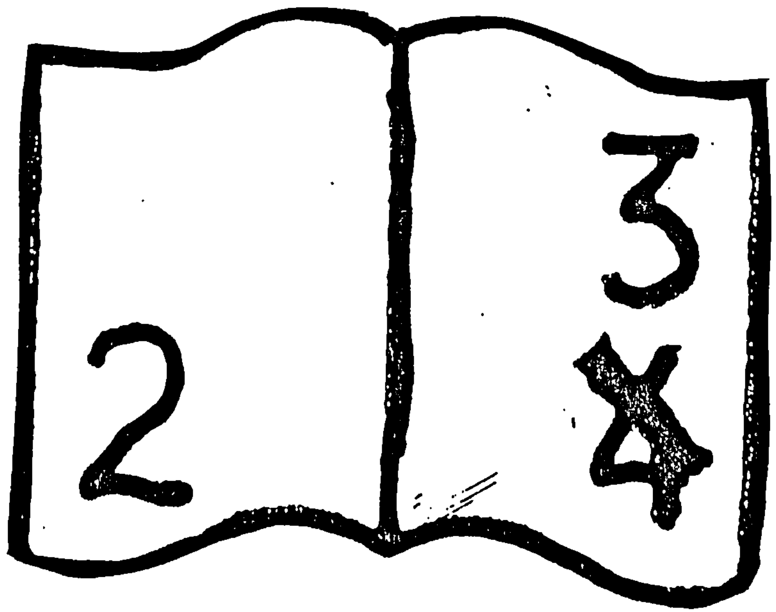


# Chapter 7: *Calluna* loss


## Abstract

Pollen and microscopic charcoal analyses of sediment cores were used to reconstruct long-term vegetation and fire histories for seven moorland lake catchments in the UK and Ireland. In each of the seven catchments *Calluna vulgaris* cover has declined considerably over the last 100-250 years. Redundancy analysis (RDA) was used to examine the statistical relationship between declining *Calluna* cover and the catchment fire histories in an attempt to determine whether burning of catchment vegetation may have caused the onset of *Calluna* loss. The results obtained suggest that burning may have been a significant factor contributing toward the decline in *Calluna* cover at only two of the seven sites studied.


## 7.1 Introduction

Britain's extensive and unique upland heather moorlands represent ecosystems of international ecological and conservation importance (Thompson *et al.*, 1993; Ratcliffe & Thompson, 1988; Webb, 1986). However, increasing numbers of studies have indicated that such upland areas have suffered considerable losses of *Calluna vulgaris*-dominated vegetation since at least the 1940s, and in many instances over much longer periods (Gimingham, 1977; Anderson & Yalden, 1981; Nature Conservancy Council, 1987; Stevenson & Thompson, 1993; Hester & Sydes, 1992). Britain is not alone in experiencing such declines in heather dominated vegetation, Sweden, Denmark, The Netherlands, Belgium, northern Germany and parts of France have also suffered considerable losses (Gimingham, 1977). These losses not only threaten considerable numbers of rare plant communities and bird species, but also the upland agricultural and sporting economies dependent upon *Calluna*-dominated moorland (Usher & Thompson, 1993; Sydes & Miller, 1988).

The extent of the '*Calluna* decline' throughout Britain has been marked. The Peak District National Park lost approximately 36% of its heather moorland between 1913 and 1981 (Anderson & Yalden, 1981); between the 1940s and the 1970s Cumbria experienced losses of approximately 286 $km^2$ (NCC, 1987); over the same period the Borders region of Scotland lost approximately 20% (368 $km^2$) of heather moorland and 71% of blanket bog (NCMS, 1991); and similarly the Grampian region lost 26% of it's heather moorland between the 1940s-1970s (NCMS, 1988).

The main explanations proposed to account for declines in heather cover are: (1) afforestation (*e.g.* Thompson *et al.*, 1988; NCMS, 1988); (2) intensification of grazing pressure, allied in most instances with poor burning management of the vegetation (*e.g.* Anderson & Yalden, 1981; Thompson & Brown, 1992; Marrs & Welch, 1991; Stevenson & Thompson, 1993); (3) atmospheric pollution and acid deposition (*e.g.* Van Dam *et al.*, 1986; Roelofs, 1986); and (4) climate change, *e.g.* the 'Little Ice Age' (Grove, 1988).

Stevenson & Thompson (1993) attempted to evaluate these hypotheses using palaeoecological techniques, and concluded that *Calluna* had most probably declined because of increased grazing pressure and prolonged burning. However, the possible influence of burning was inferred without direct palaeoenvironmental evidence of fire activity in the lake catchments studied, and thus their conclusions are somewhat speculative. The aim of this study is to further evaluate the role of past burning as a possible cause of *Calluna* loss in seven UK and Irish catchments using microscopic charcoal analyses. The alternative hypotheses pertaining to the other possible causes of *Calluna* loss outlined above are also considered and discussed.

### 7.2 Outline of methodology

The following methodology was devised to assess the possible influence of past fire activity in moorland catchments as an agent of vegetation modification, and primarily as a cause of declining *Calluna* cover.

- Short (*c.*80 cm) sediment cores were taken from seven UK and Irish lake sites.
- Vegetation histories were reconstructed by standard palynological methods (Moore *et al*, 1991). (Only the *Calluna*:Gramineae ratios are presented because they are of prime concern to this study).
- Microscopic charcoal analyses (See Chapter 3 for method) were conducted to reconstruct catchment fire histories.

- Redundancy analyses (RDA) and Monte Carlo permutation tests (Lotter and Birks, 1993; Korsman *et al.*, 1994) were used to determine statistically the extent to which burning may have been responsible for the decline of *Calluna*, and the concomitant increase of graminaceous species, in the catchment vegetation.

### 7.2.1 Site selection rationale

The seven UK and Irish lake catchments selected for study were chosen because they fulfilled a number of important criteria (See Figure 3.2 for a location map, and Section 3.1.2 for summary information on the individual sites). Each catchment is known to have experienced a significant degree of *Calluna* loss over the past few centuries (Stevenson & Thompson, 1993). All are headwater lakes, chosen in an attempt to help define the source area of charcoal entering the lake sediments, *i.e.* palynological studies have suggested that headwater lakes, with limited drainage networks, have small pollen source areas and, therefore, sediment records are likely to reflect local rather than extra-local pollen spectra (Peck, 1973; Bonny, 1976; Jacobson & Bradshaw; Birks *et al.*, 1990). A similar line of reasoning is adopted for microscopic charcoal, *i.e.* that the lake sediment records of the lakes studied should contain charcoal of a predominantly local origin, and thus provide histories of fire activity within their respective catchments (See also Chapter 5). The distribution of the sites from North Wales through to the north of Scotland and into Ireland and Northern Ireland allows some assessment of whether regional patterns, both in the timing and possible causes of declining *Calluna* cover, exist.

### 7.2.2 Dating of the sediment cores

Chronologies for the upper sediments of all the cores were constructed using the $^{210}$Pb CRS model (Appleby & Oldfield, 1978). Figures 6.1 and 6.2 present the $^{210}$Pb age/depth profiles for the seven sites (the chronologies and accumulation rates are presented in tabular form in Appendix 6). The Round Loch of Glenhead and Loch Teanga cores were also dated using $^{14}$C methods (Jones *et al.*, 1987; Jones *et al.*, 1989). Nineteen $^{14}$C dates on bulk peat samples were conducted on the Round Loch of Glenhead core and ten were performed on the Loch Teanga core (Appendix 6).

The dates of the loss on ignition increases which lie below the portions of the cores dated directly by $^{210}Pb$ methods were estimated by extrapolation. It is acknowledged that such a method is built upon the assumption that accumulation rates have remained relatively constant over extended periods, but without additional dates further down the cores it represents the best available method. The $^{210}Pb$ derived age/depth profiles for Lough Muck, Loch Na Larach and Llyn Conwy which show strong, statistically significant, linear relationships and thus the $^{210}Pb$ chronologies were extrapolated to the core bases using a simple linear regression model. The $^{210}Pb$ chronologies for Blue Lough and Loch Tanna, however, display exponential age/depth profiles, for these sites extrapolations were based on the lowermost portions of the curves where significantly linear relationships exist. The dates estimated in this fashion have potentially large error margins, with perhaps correspondingly greater errors on progressively earlier dates, therefore, all dates should be taken as approximations with minimum errors of at least ±50 years.

At Round Loch of Glenhead and Loch Teanga where $^{14}C$ dates were available in addition to $^{210}Pb$ chronologies the dates of LOI increases were estimated by regression after amalgamating the two chronologies. At Round Loch of Glenhead, however, a number of the dates are believed to have been contaminated by older carbon (Stevenson *et al.*, 1990) and thus are unreliable. Consequently only the dates from the lower most sections of the core, and the youngest dates which appear to be free from older carbon errors, were used in the age estimations (Stevenson *et al.*, 1990). The dates estimated in this manner are again subject to considerable sources of error and thus must be treated with caution and with potentially large errors.

### 7.2.3 Statistical analyses

The possible influence of fire activity as a cause of *Calluna* loss in the catchments of the seven lake sites studied was assessed by canononical ordination techniques (Birks & Lotter, 1993; Korsman *et al.*, 1994). The charcoal data, as proxy measures of reconstructed fire activity, were used as 'environmental' or predictor variables to explain statistically the *Calluna*:Gramineae ratios. Detrended canononical correspondence analysis

(DCCA) was used to ascertain whether linear (redundancy analysis; RDA) or unimodal (canononical correspondence analysis; CCA) ordination methods were appropriate (Hill & Gauch, 1980). The gradient lengths of the first DCCA axis for all of the LOI profiles were short (<1.5 SD) and so RDA was used (ter Braak & Prentice, 1988). The statistical significance of the RDA analyses were assessed by restricted Monte Carlo permutation tests for stratigraphically ordered data (ter Braak, 1990a), four hundred and ninety-nine permutations were used for each test (John Birks, pers. comm.). The computer program CANOCO 3.12 (ter Braak, 1990b) was used to perform all calculations and analyses.

## 7.3 Results

### 7.3.1 Pollen profiles (*Calluna*:Gramineae ratios)

Figure 7.1 is a composite diagram of the *Calluna*:Gramineae pollen ratios from all of the seven sites studied. The *Calluna*:Gramineae ratio represents an approximate index of *Calluna* loss and replacement by graminaceous species (Stevenson & Thompson, 1993). The majority of the *Calluna* and grass pollen in the samples is believed to have been derived from the immediate lake catchment, from *Calluna*-dominated moorland and blanket bog communities (Evans & Moore, 1984; Sugita, 1993, 1994; Bradshaw, 1994). The Gramineae counts are believed to represent the sum of the main acid grassland species, *i.e. Molinia caerulea, Agrostis stolonifera, A. canina, Festuca* spp. and *Nardus stricta* (Stevenson & Thompson, 1993).

All of the *Calluna*:Gramineae ratio profiles presented (Figure 7.1) have considerable declines in their upper profiles, and although some experience minor fluctuations in their lower profiles the most recent declines in the *Calluna*:Gramineae ratios are much more marked and persistent and exhibit little sign of recovery. Loch Na Larach, Lough Muck, Llyn Conwy and Loch Teanga exhibit declines of between 25-30%, whilst the declines at Blue Lough, Round Loch of Glenhead and Loch Tanna are more marked (40-50%). Considerable changes in the relative proportions of *Callunetum* and grasses have obviously occurred in the lake catchments.

Figure 7.1: Summary diagram of *Calluna*:Gramineae ratio profiles from the seven UK and Irish sites studied.

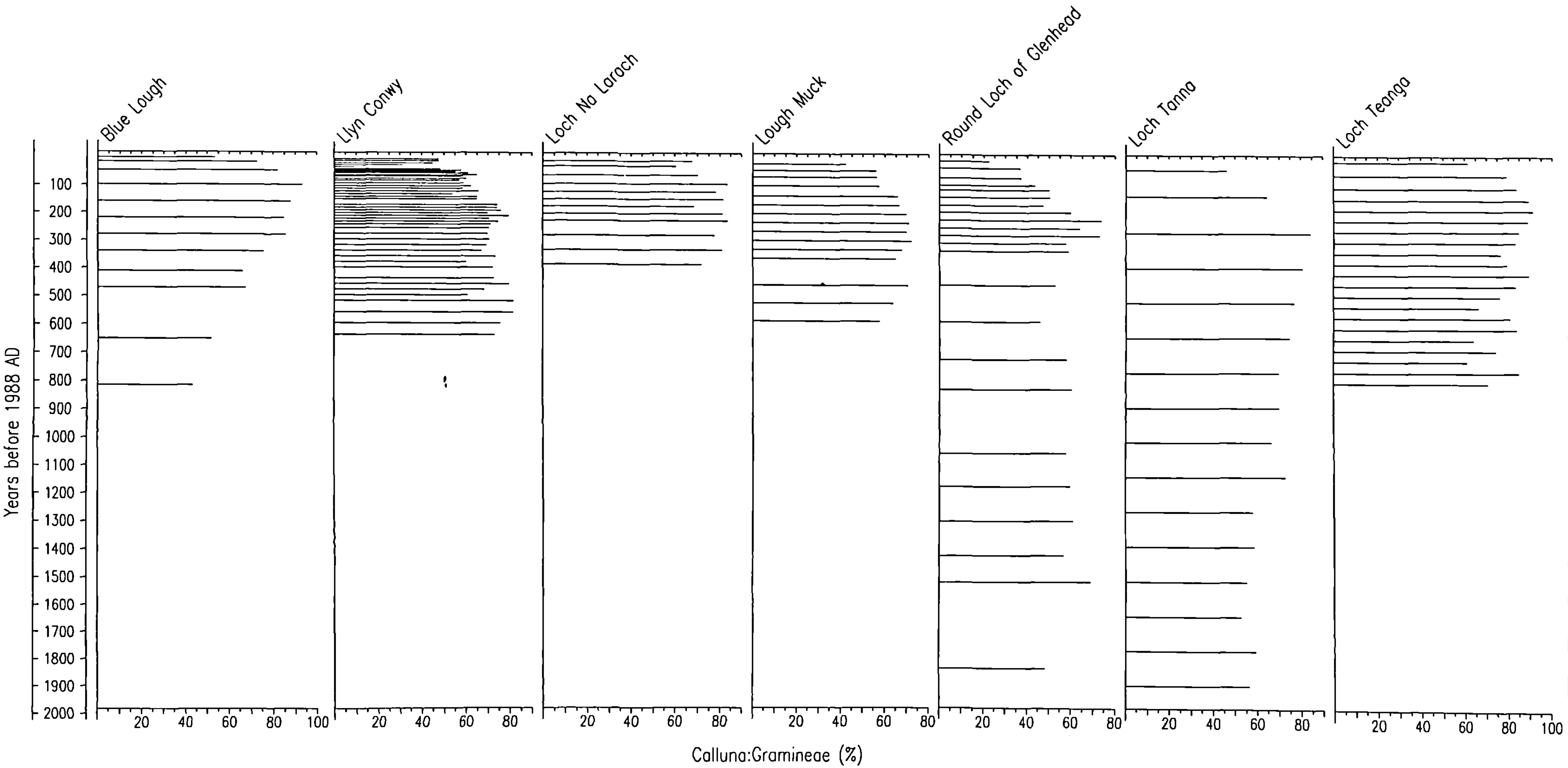


Table 7.1: Approximate dates of the onset of the *Calluna* declines at the seven sites studied. The sites are listed in chronological order of the onset of the *Calluna* decline.

| Site | Onset of *Calluna* decline (years AD) |
|---|---|
| Round Loch of Glenhead | 1770 |
| Llyn Conwy | 1780 |
| Lough Muck | 1790 |
| Loch Tanna | 1800 |
| Loch Teanga | 1810 |
| Blue Lough | 1890 |
| Loch Na Larach | 1900 |

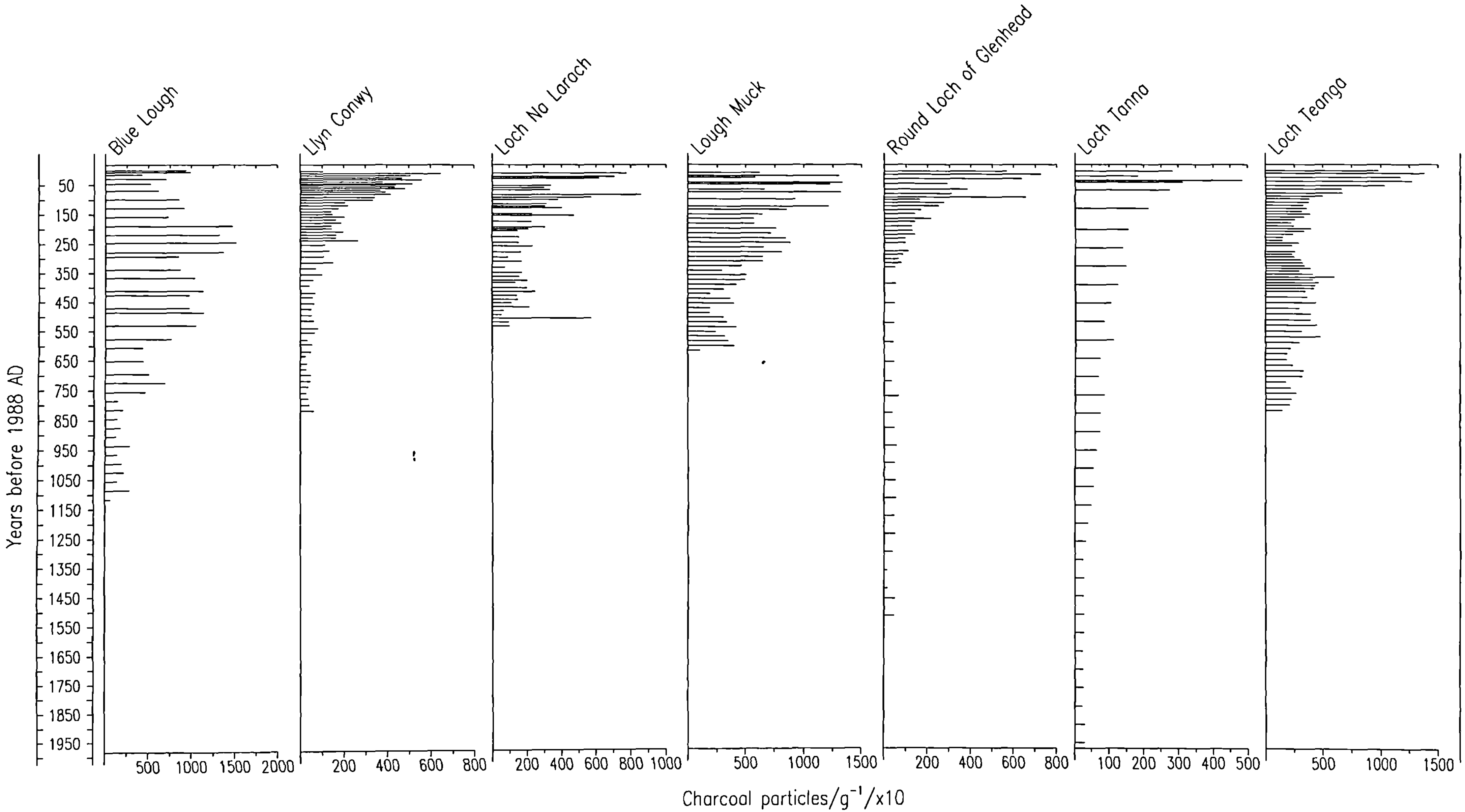
The declines of *Calluna* at Round Loch of Glenhead, Llyn Conwy, Lough Muck, Loch Tanna and Loch Teanga all began within approximately 40 years of each other, between *c.*1770-1810 AD. The *Calluna*:Gramineae declines at Blue Lough and Loch Na Larach commenced approximately 80-110 years later between *c.*1890-1900 AD.

### 7.3.2 Charcoal profiles

The charcoal profiles for the seven cores are presented collectively in Figure 6.4. In this diagram charcoal abundance is taken as an approximate measure of fire activity in the immediate lake catchment as the majority of microscopic charcoal produced by moorland fires is believed to be deposited within a hundred metres of parent fires. Although it is accepted that a small proportion of the charcoal produced may be dispersed extra-locally or even regionally (Clark, 1988a), the overwhelming proportion of charcoal in the lake sediment cores sampled is hypothesised to have local origins (Sugita, 1993, 1994) (see Section 2.3.3).

In the Blue Lough sediment core charcoal levels remain relatively low below 56cm (*c.*1200-1250 AD) before catchment burning levels increased gradually through to 38 cm

Figure 7.2: Summary diagram of microscopic charcoal profiles from the seven UK and Irish sites studied.



(*c.*1500 AD). The period between 35-18 cm (*c.*1500-1800 AD) has sustained high charcoal abundance suggesting it was the period of greatest fire activity in the catchment. Over the past century burning activity fell, although in the last decade fire activity increased again. At Llyn Conwy prior to 57 cm (*c.*1750 AD) charcoal values are low and fairly constant denoting relatively low levels of catchment burning activity. A period of moderate intensification of burning activity prevailed between 57-29 cm (*c.*1750-1900 AD), and post-1900 fire activity (above *c.*29 cm) in the catchment intensified further.

With the exception of a large peak in charcoal abundance at 76 cm (*c.*1480 AD) fire activity in the Loch Na Larach catchment prior to *c.*1800-1850 AD was considerably less intensive than during more recent times. In the Lough Muck catchment fire activity has been significantly greater in the last couple of centuries (above *c.*22 cm) than previously, although the period between 47-30 cm (*c.*1650-1800 AD) also experienced increased levels of burning compared with the preceding three centuries. The Round Loch catchment experienced consistently low levels of fire activity between 90-45 cm (*c.*400-1700 AD), between 45-28 cm (*c.*1700-1800 AD) charcoal levels were marginally but consistently higher, and in the post-1800 AD period charcoal levels have been much higher suggesting an increase of fire activity in the catchment.

The Loch Tanna charcoal record is similar to that from the Round Loch, high charcoal values during the past hundred years (above *c.*7 cm) suggest a high intensity of fire management, whilst fire activity was relatively low prior to this time, with fire activity increasing only gradually through the 14th and 15th centuries. The Loch Teanga charcoal profile exhibits the familiar (present in all but Blue Lough) period of intensive fire activity in the post-1900 period (above 14 cm), prior to *c.*1900 AD fire activity in the catchment was less intensive.

### 7.3.3 Results of statistical analyses

The results of the redundancy analyses of the biostratigraphical data sets at the seven sites are presented in Table 7.2 as exact Monte Carlo significance values (499 permutations) (Korsmann *et al.*, 1994).

Table 7.2: Results of the redundancy analyses and Monte Carlo permutation tests to assess the extent to which catchment fire activity explained *Calluna* loss. Entries are percentages of variance explained by the first canononical axis and significance levels as assessed by restricted Monte Carlo permutation tests (499 permutations).

| Site | Predictor | % variance in *Calluna*:Gramineae ratio explained by first RDA-axis | Significance of explained variance (p-value) |
|---|---|---|---|
| Blue Lough | Charcoal | 23 | 0.400 |
| Lough Muck | Charcoal | 30 | 0.060 |
| Llyn Conwy | Charcoal | 47 | 0.002 |
| Loch Na Larach | Charcoal | 24 | 0.080 |
| Round Loch of Glenhead | Charcoal | 54 | 0.002 |
| Loch Tanna | Charcoal | 0 | 0.868 |
| Loch Teanga | Charcoal | 5 | 0.334 |

At only two of the sites, Llyn Conwy and Round Loch of Glenhead, were there highly significant relationships (p = <0.01) between changes in catchment burning (reconstructed using microscopic charcoal) and the decline of *Calluna* cover as assessed by restricted Monte Carlo permutation tests. At Lough Muck and Loch Na Larach the significance of the explained variance in the *Calluna*:Gramineae ratios, p = 0.06 and p = 0.08 respectively, were only marginally non-significant at the 95% level, but Loch Teanga, Loch Tanna and Blue Lough exhibited no significant relationship between the pollen and charcoal variables.

The percentages of variance in the *Calluna*:Gramineae ratio profiles explained by the charcoal indices were greatest at Llyn Conwy (47%) and Round Loch of Glenhead (54%), *i.e.* those which displayed statistically significant relationships. At Loch Muck (30%), Loch Na Larach (24%) and Blue Lough (23%) notable amounts of the variance in the pollen profiles were accounted for by the charcoal indices, but at Loch Teanga (5%)

and Loch Tanna (0%) nominal amounts of variance in the pollen profiles were explained by the first RDA axis.

### 7.4 Discussion: The possible causes of the *Calluna* decline

#### 7.4.1 Fire activity

Controlled periodic burning has been practised for many centuries to maintain heather dominance in large areas of the British and Irish uplands. If conducted on the correct temporal rotation it is very effective (Gimingham, 1972), however, inappropriate periodic burning can adversely affect *Calluna*-dominated communities in a manner similar to that caused by grazing (Rawes & Williams, 1973; Miles *et al.*, 1978) and both over-burning and under-burning can have potentially detrimental effects on *Calluna* cover (Miles, 1988; Hester & Sydes, 1992). The ecological consequences of burning alone are, however, extremely difficult to assess because the effects of grazing activity are an 'all pervasive' presence in UK and Irish moorland areas (Miles, 1978).

A number of studies have sought to determine the effects of fire on *Callunetum*. Burning *Calluna*-dominated stands on mineral soils at 3-6 year intervals have been found to tend to shift dominance to grasses, especially *Deschampsia flexuosa* on well drained soils and *Molinia caerulea* on poorly drained soils (Miles, 1988). A fire frequency of 6-10 years favours *Erica cinerea* and *E. tetralix*, and a rotation of about 10-20 years favours *Calluna* (Miles, 1988). On peat, however, a 20-year frequency may favour *Eriophorum vaginatum* at the expense of *Calluna* (Taylor & Marks, 1971; Hobbs, 1984). Such figures can only be taken as gross generalisations because variations in plant productivity can vary enormously in response to local environmental conditions but they do provide useful indicators of the possible directions and approximate timescales of change.

Infrequent uncontrolled fires may also bring about succession of grasses at the expense of *Calluna*. Intense fires which destroy the upper organic horizons of the soil or peat may remove not only the stem bases and rhizomes from which *Calluna* regenerates after low intensity fires, but also the soil seed bank (Maltby, 1980; Imeson, 1971). *Calluna* can eventually re colonise patches of ground bared by intense fire, but sheep grazing tends to favour the establishment of grasses (Grant & Hunter, 1968). Heather grows from apical meristems and so is unable to withstand continued heavy grazing as well as grasses which grow continually from basal meristems (Philips *et al.*, 1981; Sydes & Miller, 1988). Sheep find young heather particularly palatable and graze it heavily in newly colonised areas following fire (Grant *et al.*, 1978), and therefore, under continual grazing grasses tend to gain dominance on intensively burned areas. In the absence of grazing pressure, however, in most instances *Calluna* will eventually regain dominance, as demonstrated by large numbers of exclosure experiments (*e.g.* Fenton, 1936; Hewson, 1977; Miles *et al.*, 1978; Rawes & Hobbs, 1979; Rawes, 1983).

The analyses conducted in this study represent an attempt to assess whether excessive burning of the *Calluna* dominated catchment vegetation, over an extended period of several centuries, may have been responsible for the observed declines of *Calluna* cover and replacement by graminaceous species. The results of the palaeoenvironmental (Figures 7.3 - 7.9) and statistical analyses (Section 7.3) suggest that increased fire activity during the last 200-250 years in the Llyn Conwy and Round Loch of Glenhead catchments may have been important in promoting the demise of *Calluna* cover. The statistically significant relationship between the charcoal and pollen indices, assessed by RDA and restricted Monte Carlo permutation tests, and the fact that approximately half of the variance in the *Calluna*:Gramineae ratio profiles is explained by the charcoal variables at these sites suggest that the influence of fire on the catchment vegetation may have been strong. However, *c.*50% of the variance in the vegetation change is not accounted for by the charcoal variable, and thus a combination of other factors, perhaps atmospheric pollution, climate change or livestock grazing, may also have contributed to the *Calluna* decline.

At Lough Muck and Loch Na Larach the results of the redundancy analyses are not statistically significant at the 95% level as assessed by Monte Carlo permutation tests, although marginally so. The Monte Carlo p-values of 0.06 and 0.08 (Table 7.1), and percentages of variance explained of 30% and 24% respectively, do however, suggest that increased fire activity during the past 100-200 years may have contributed to some degree to declining *Calluna* cover in these catchments. Possible alternative causes of *Calluna* loss need to be assessed before the full importance of changing fire regimes on the vegetation

Figure 7.3: *Calluna*:Gramineae ratio and microscopic charcoal profiles for Blue Lough.

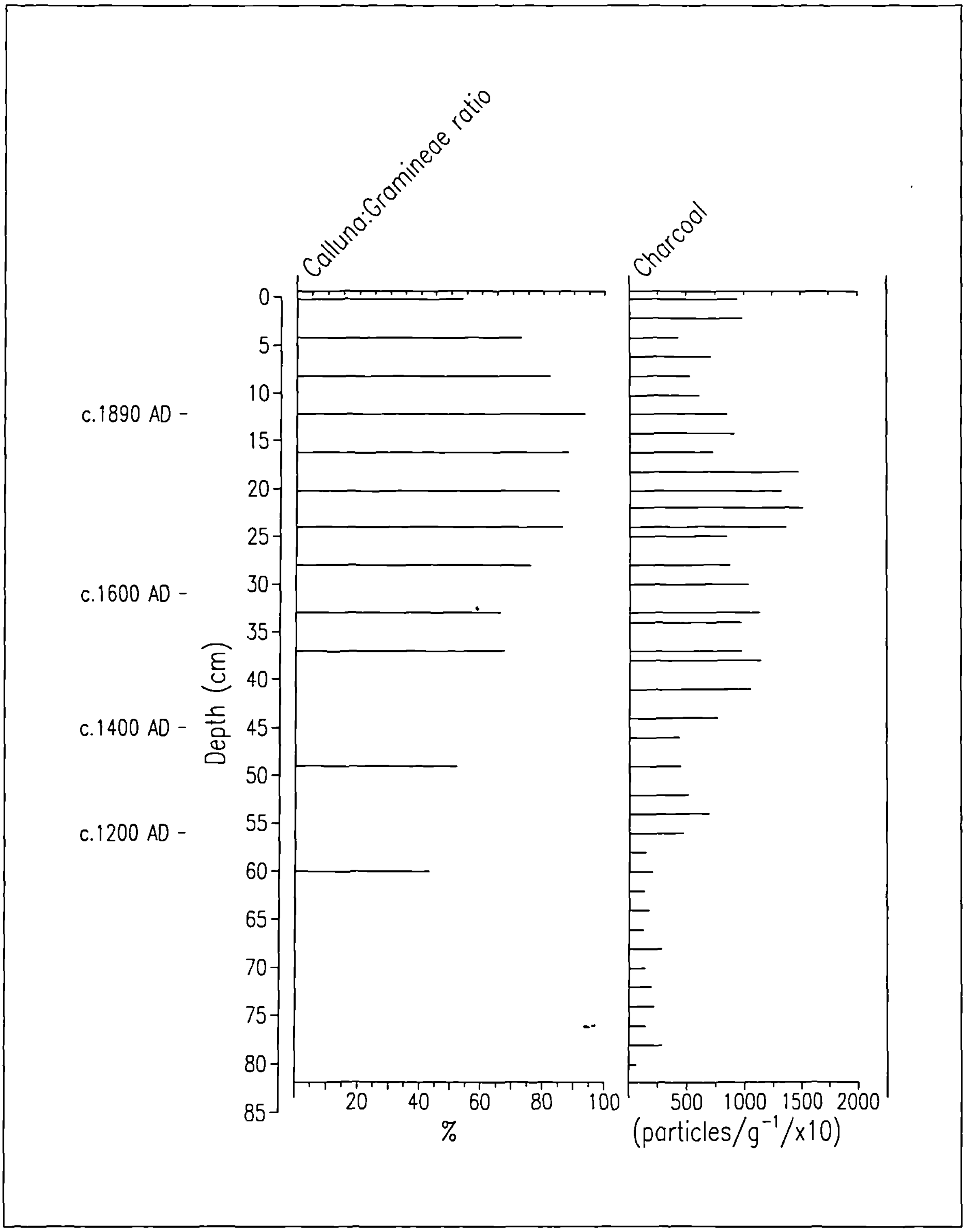


Figure 7.4: *Calluna*:Gramineae ratio and microscopic charcoal profiles for Llyn Conwy.

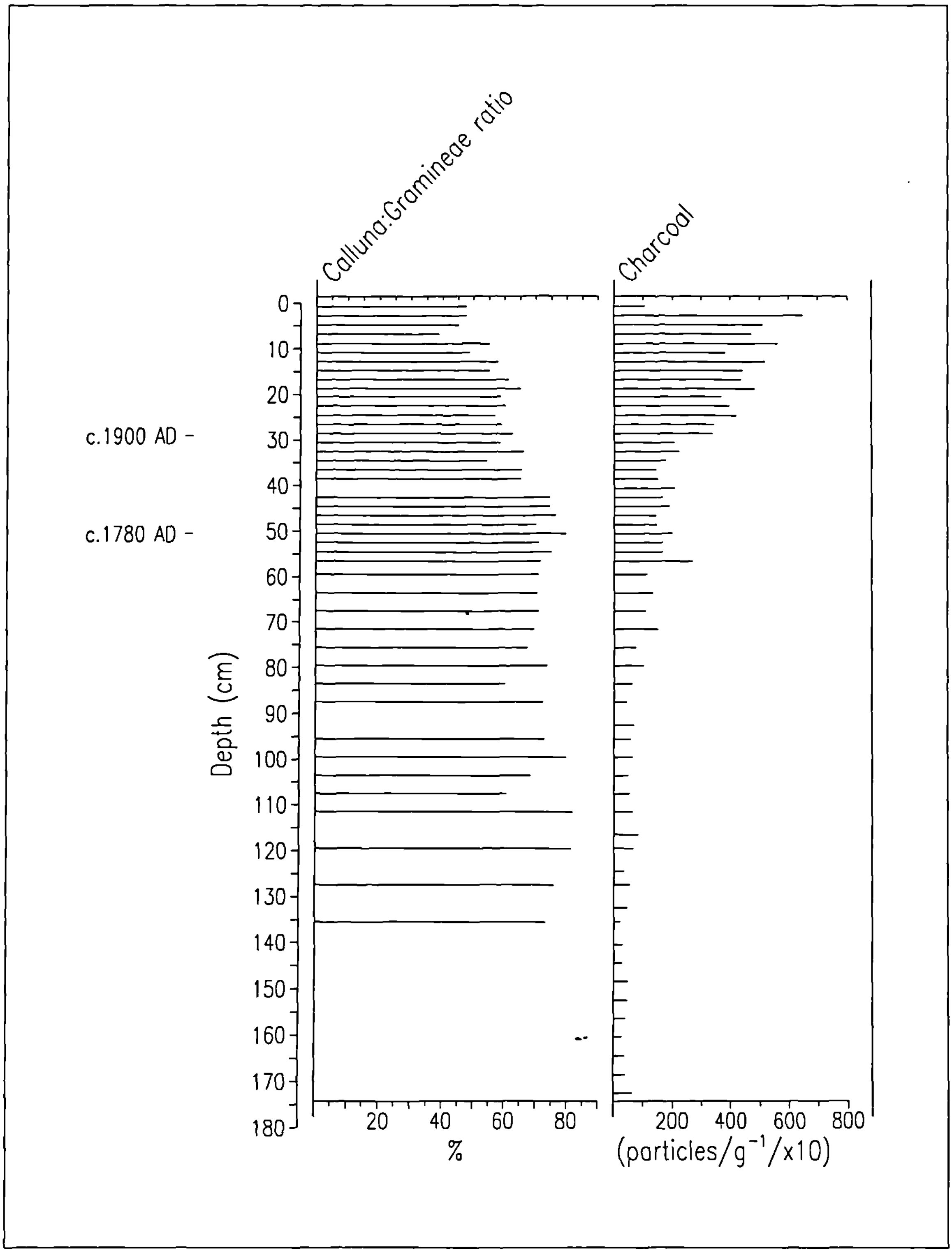


Figure 7.5: *Calluna*:Gramineae ratio and microscopic charcoal profiles for Loch Na Larach.

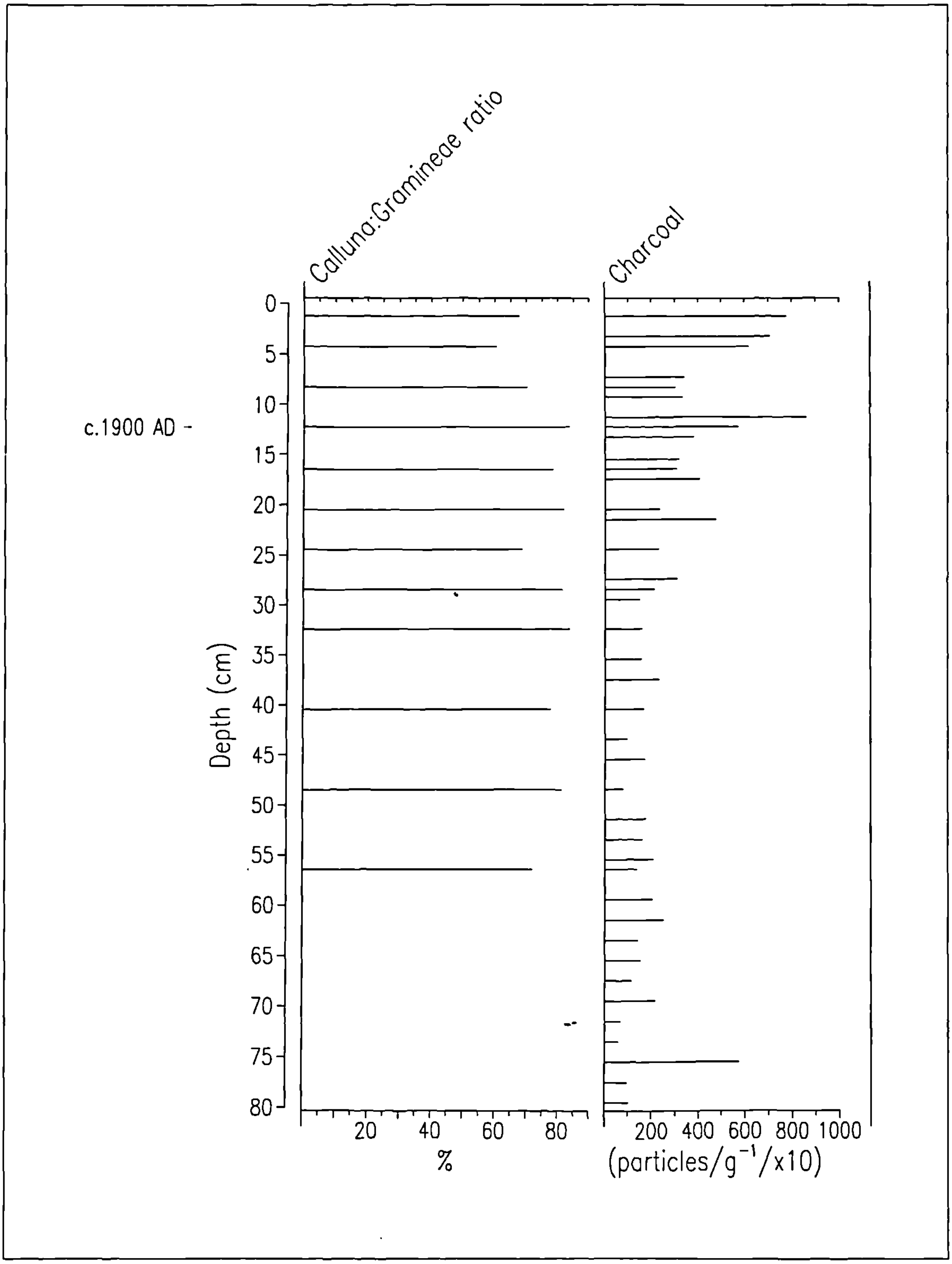


Figure 7.6: *Calluna*:Gramineae ratio and microscopic charcoal profiles for Lough Muck.

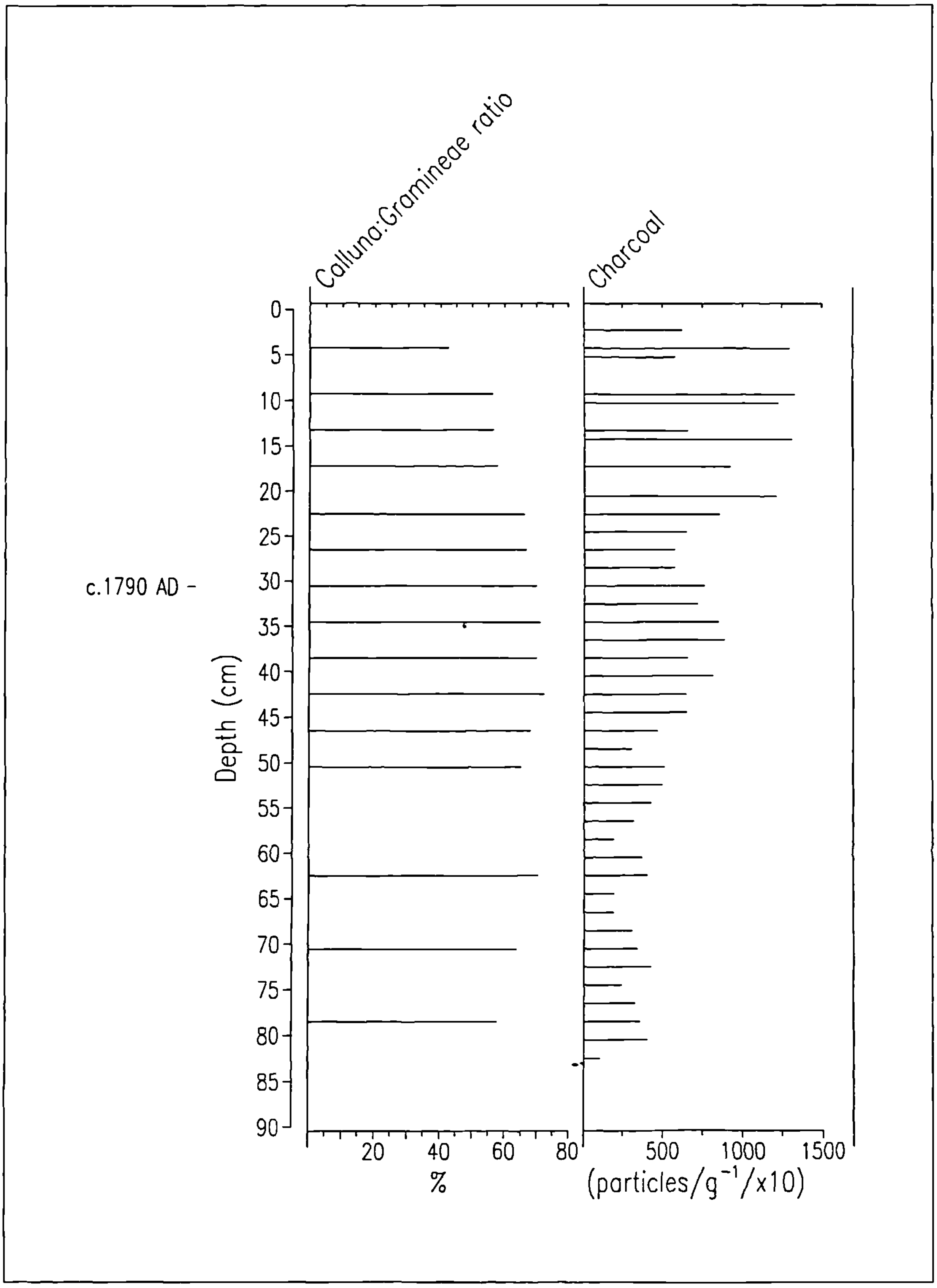


Figure 7.7: *Calluna*:Gramineae ratio and microscopic charcoal profiles for Round Loch of Glenhead.

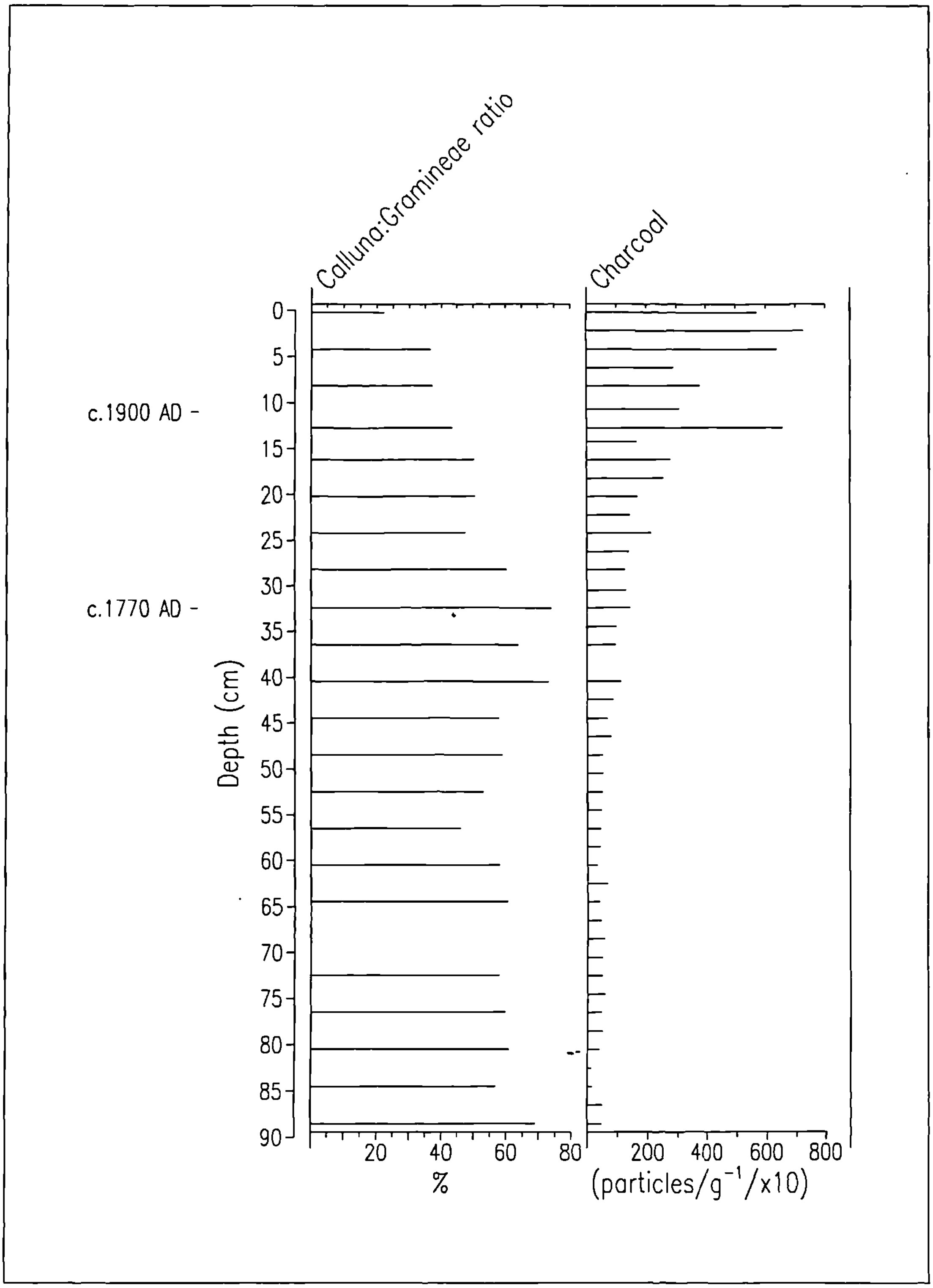


Figure 7.8: *Calluna*:Gramineae ratio and microscopic charcoal profiles for Loch Tanna.

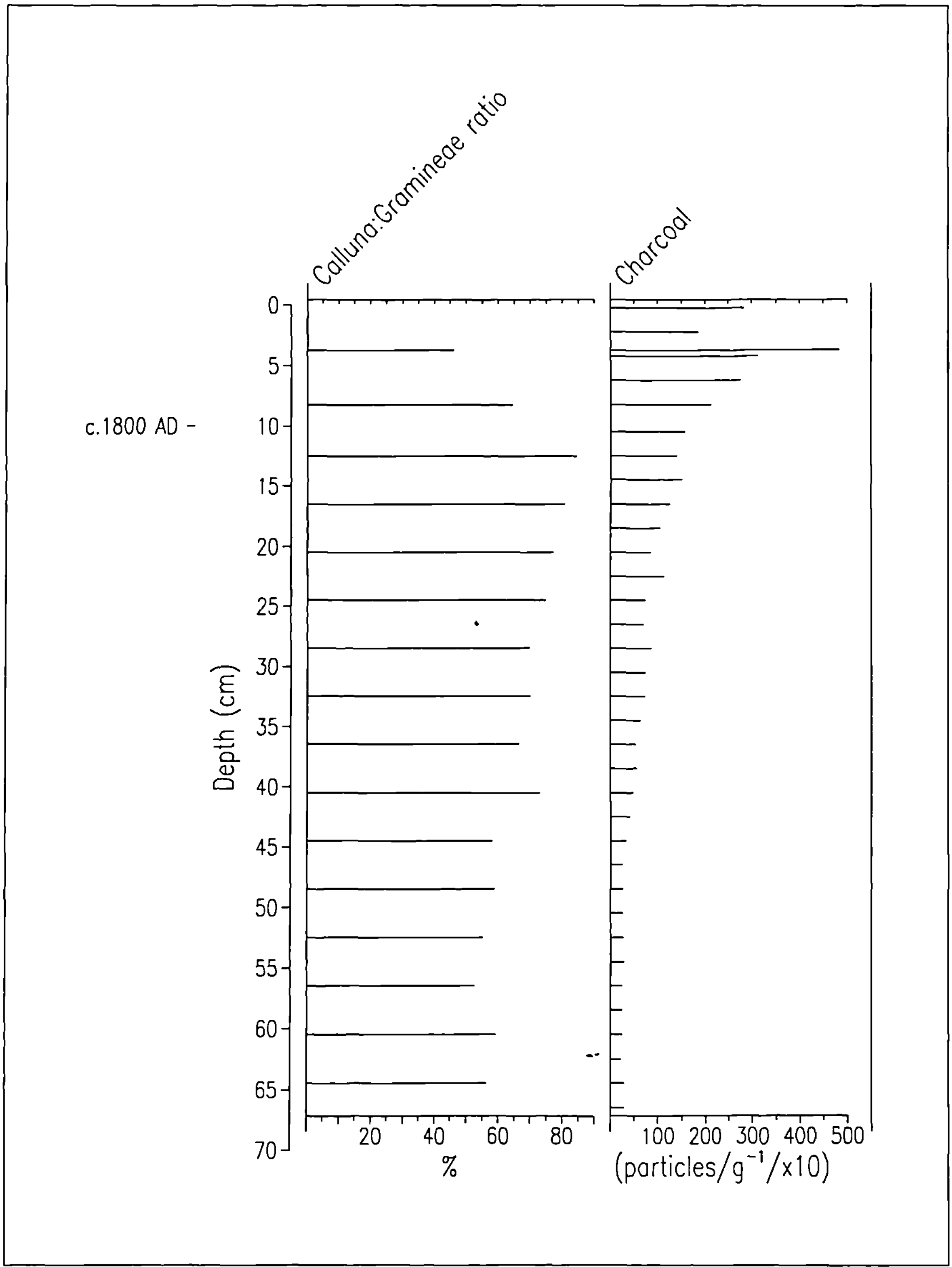
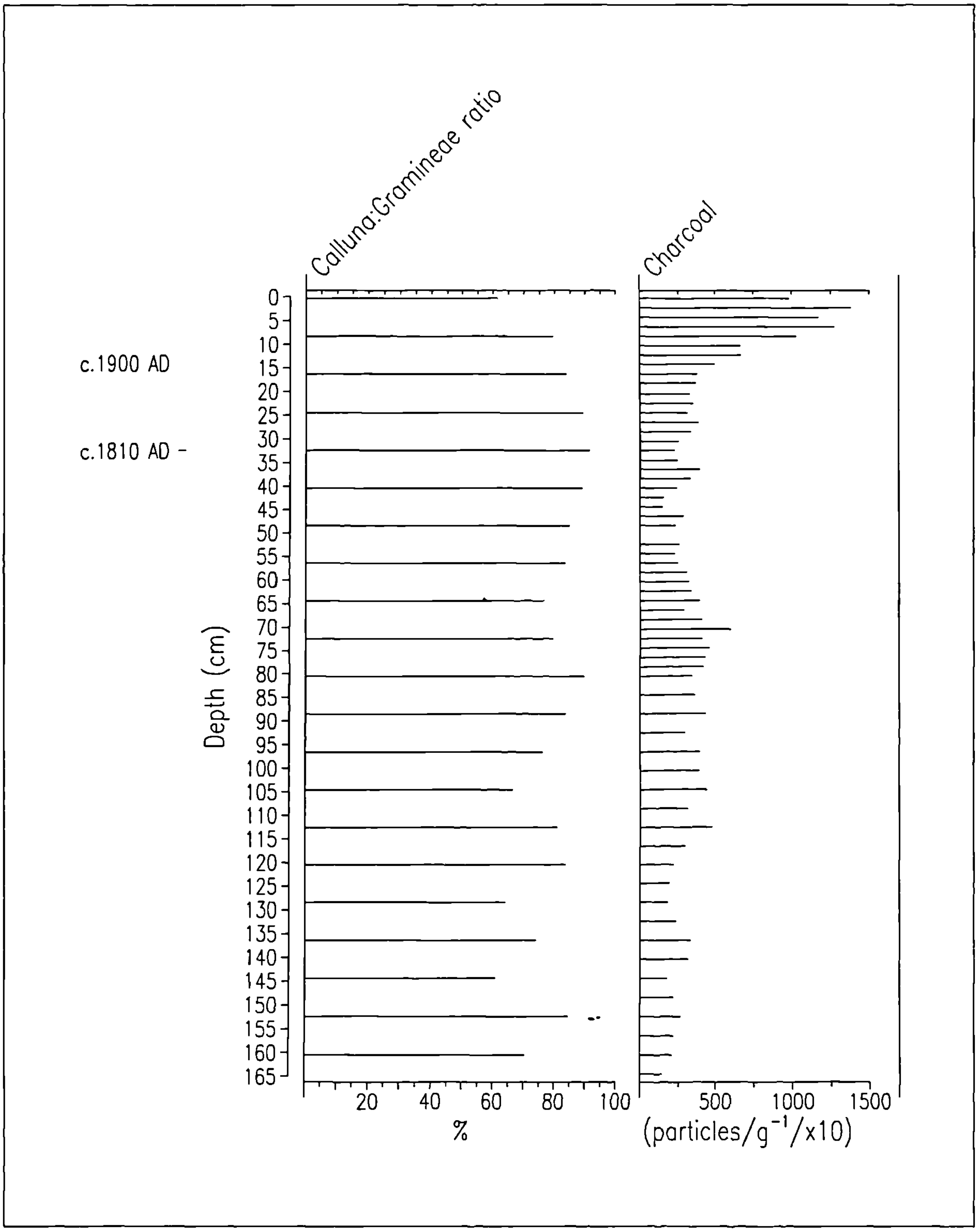


Figure 7.9: *Calluna*:Gramineae ratio and microscopic charcoal profiles for Loch Teanga.



in the catchments can be fully addressed. At Blue Lough, Loch Tanna and Loch Teanga fire activity does not appear to played an important role in causing the decline of *Calluna*, the statistical relationships between fire activity and vegetation change are not significant, alternative explanations must therefore be sought.

### 7.4.2 Afforestation

At least 1.1 million ha of former upland moorland in Britain has been afforested since 1924, a major loss of heather dominated vegetation (Sydes & Miller, 1988). Losses to forestry have been particularly great in Scotland, where between the 1940s and 1970s afforestation accounted for approximately 62% of the total reduction in semi-natural upland vegetation (Tudor & Mackey, 1995). However, whilst afforestation does account for considerable amounts of *Calluna* loss on a nation wide scale, in the seven catchments studied *Calluna* abundance declined well before the aforementioned expansion in forestry, and none of the catchments have notable areas of coniferous plantation. In addition afforestation does not account for the apparent expansion of graminaceous species at the expense of heather cover. The declines in *Calluna* cover in these catchments, and over much of the remainder of Britain and Ireland (Stevenson & Thompson, 1993) are, therefore, assumed not to be the result of afforestation.

### 7.4.3 Atmospheric pollution

Anthropogenically derived atmospheric pollution, and acidic pollutants in particular, have been implicated in the acidification of upland lakes and the decline of *Sphagna* and lichens in some upland ecosystems (*e.g.* Gilbert, 1968; Ferguson *et al.*, 1978; Battarbee *et al.*, 1985; Battarbee *et al.*, 1988; Battarbee *et al.*, 1990; Edwards *et al.*, 1990). The effects of atmospheric contaminants on higher semi-natural terrestrial plant communities, however, is rather less certain (Ferguson & Lee, 1983; Press *et al.*, 1983; Lee *et al.*, 1988).

Press *et al.* (1983) note the decline of heather cover in the Peak District, an area of extremely high pollutant deposition in the past (Tallis, 1964; Lee & Tallis, 1973), and suggest that pollution may have played a role in its demise. Unsworth *et al.* (1988), however, suggest that drainage and burning may have been more important in adversely affecting the growth of *Calluna* over the same period and that an explanation involving atmospheric pollution as the sole causal factor could not be reasonably upheld. Chambers *et al.* (1979) attributed the onset of a decline in *Calluna* cover and its replacement by grasses, particularly *Molinia caerulea*, in South Wales during the 19th century to acidic atmospheric pollutant deposition. However, Stevenson & Thompson (1993) express scepticism over the chronology of events presented, and suggest that although pollution may have compounded the decline of *Calluna* that it is unlikely that it caused its inception. Rather more robust evidence of the potential impact of atmospheric pollution on heathland vegetation is provided by studies in The Netherlands where the spread of grasses at the expense of heather has been attributed to nitrogen deposition (Roelofs, 1986; Van Breemen & van Dijk, 1988).

In The Netherlands, however, the estimated inputs of $NH_3$ and $NO_x$, to terrestrial ecosystems are amongst the highest in the world, and as a consequence grasses (*Molinia caerulea, Deschampsia flexuosa* and *Festuca ovina*) have expanded in heathlands at the expense of *Calluna vulgaris* and *Erica tetralix* (Van Dam *et al.*, 1986; Roelofs, 1986). Van Breemen & van Dijk (1988) suggest that 'the change of heathlands into grasslands is undoubtedly caused by an increased availability of nutrients in the soil (De Smidt, 1983; Roelofs *et al.*, 1984), which in turn is the result of an increased nutrient input from atmospheric deposition and decreased output due to decreased utilisation of heather'. *Calluna* declines relative to grasses under high nitrogen loads because it undergoes important physiological changes which increase its sensitivity to frost and drought (Heil, 1984), and the increased nutritive value of its leaves encourage attack by the heather beetle (*Lochmaea suturalis*) (Brunsting and Heil, 1985; de Smidt, 1995). Mass development of grasses occurs at nitrogen inputs exceeding 20-30 kg $ha^{-1}$ $year^{-1}$ (Roelofs, 1986; Soderlund & Granat, 1982; Rodhe & Rood, 1986).

Sulphur dioxide concentrations in British rain have fallen during the last few decades, however, nitrate pollution has become a more marked problem. The total deposition rate for nitrogen is currently around 20-30 kg $ha^{-1}$ $year^{-1}$ across much of Britain (Pitcairn *et al.*, 1991). Even in remote areas, such as north-west Scotland, west Wales and south-west England, wet-deposited nitrogen has increased by about 50% since *c.*1950 (Pitcairn *et al.,* 1991). In recent decades, nitrogen may have had some impact upon higher terrestrial plant communities in the British uplands, however, there is not yet any unequivocal evidence to support this (Lee *et al.*, 1988). Thompson and Baddeley (1991) do, however, suggest that in the future British *Calluna vulgaris - Eriophorum vaginatum* blanket mire, *Calluna vulgaris - Vaccinium myrtillus - Sphagnum capillifolium* heath, *Calluna vulgaris - Racomitrium lanuginosum* heath, and *Calluna vulgaris - Juniperus communis* sp. *nana* heath communities may be increasingly at risk from atmospheric pollution.

The evidence reviewed illustrates that atmospherically derived pollutants may have contributed to compounding *Calluna* losses and promoting the increase of grasses in areas of high deposition over recent decades, however, it is extremely unlikely that atmospheric pollution alone has been responsible for initiating and maintaining the heather declines experienced in the catchments studied. At most of the sites the onset of the *Calluna* declines pre-date the accepted start of extensive industrial pollutant emissions, *c.*1850 AD (Rippey, 1990; Williams, 1991), and in addition most of the sites are located in regions relatively remote from the pollutant loads necessary to cause possible significant vegetation change of the scale noted (*i.e.* > c.20 kg N $ha^{-1}$ $year^{-1}$; Williams *et al.*, 1989; Woodin & Farmer, 1993; Thompson & Baddeley, 1991).

### 7.4.4 Climate change

Stevenson & Thompson (1993) dismiss the possibility that climatic change may have been responsible for initiating declines in *Calluna* cover, because the onset of the declines generally post-date the most severe climatic conditions of the Little Ice Age (*c.*1550-1850; Grove, 1988). Such an argument can be maintained for Blue Lough and Loch Na Larach where the *Calluna* decline did not begin until *c.*1890-1900, however, for the other five sites such an explanation is rather less readily sustained.

The 'Winter and Summer severity indices' produced by Lamb (1977; 1982) illustrate that the harsh climatic conditions of the Little Ice Age persisted into the mid-19th century before general, sustained warmth returned to Britain, and it was not until the late-

1800s to early-1900s that eventual lasting climatic amelioration and stability was reached (Lamb, 1977; 1982). The onset of the *Calluna* declines at Round Loch of Glenhead, Llyn Conwy, Lough Muck, Loch Tanna and Loch Teanga (*c.*1770-1810 AD) all occur well within the predominantly colder and wetter conditions of the Little Ice Age.

*Calluna vulgaris* (L.) Hull is relatively ecologically tolerant to climatic and topographic controls, a point well illustrated by its current wide ranging distribution, *i.e.* lowland and upland heaths, moors and bogs, open *Pinus*, *Betula* and certain types of *Quercus* wood, fixed sand dunes and even partially stabilised scree (Gimingham, 1960). *Calluna* is also tolerant of a wide range of temperature and length of growing season, and to a certain extent water content of soils, although growth is best where the soils are at least moderately well drained and establishment and growth are much reduced in water-logged soils. Although extreme frost may adversely affect young plants, the present day distribution of *Calluna* into the northern extremity of Norway and Iceland suggest that it is relatively frost resistant (Gimingham, 1960).

*Calluna* is a particularly hardy upland species and it is unlikely that the generally colder climatic conditions of the late-18th and early-19th could have caused the declines of the species on the scale recorded since this period. The wetter conditions experienced during this time may have had a widespread detrimental effect on *Calluna* communities on bogs and other marginal sites, *i.e.* Forest & Smith (1975) have shown that a significant negative relationship exists between the productivity of vascular plants on blanket bog and increasing wetness, however, such a factor is unlikely to have caused the demise of *Callunetum* on the scale witnessed (Stevenson & Thompson, 1993).

Therefore, it can be concluded that it is unlikely that climatic change alone has been responsible for the decline of *Calluna* observed in the lake catchments. If climatic factors were the sole cause of the *Calluna* decline, why-was the onset not earlier during the equally, if not more, severe conditions between *c.*1500-1700 AD? And why did the *Calluna* declines at all of the sites not occur synchronously? The harsh climatic conditions of the Little Ice Age (Grove, 1988) may, however, have compounded the effects of other factors by providing conditions which stressed plant growth.

### 7.4.5 Grazing

'Loss of heather has occurred as a result of overgrazing by sheep' (Grant & Armstrong, 1993), a bold statement highlighting the conviction held by the authors that the impact of sheep grazing on *Calluna* cover has been indisputable. This view is supported by large numbers of controlled grazing studies performed throughout the British uplands: *e.g.* Rawes & Hobbs (1979); Birnie & Hulme (1990); Grant *et al.* (1985); Miles *et al.* (1978); Welch & Rawes (1966). Such studies indicate consistently that sheep grazing is a very important factor controlling upland vegetation development and moorland community structure.

At low densities sheep grazing can increase *Calluna* cover and shoot production on both dry heath and blanket bog (Rawes & Williams, 1973; Hewson, 1977), and Rawes & Hobbs (1979) even suggest that on blanket bog light grazing without burning may be the optimum management strategy. However, sheep densities in the range of >2.7 sheep $ha^{-1}$ on dry heath (Welch, 1984) and 0.4-0.5 sheep $ha^{-1}$ on blanket bog (Welch & Rawes, 1966; Rawes & Hobbs, 1978) are believed to be detrimental to *Calluna* development and favour the spread of grasses (Nolan *et al.*, 1995; Fenton, 1933; Heddle & Ogg, 1933). Such changes in vegetation composition can be very rapid, *i.e.* *Calluna*-dominant dwarf-shrub heath can be succeeded by *Agrostis-Festuca* grassland in only 2-3 years with heavy grazing and trampling by livestock (Miles *et al.*, 1978). The replacement of heather by grasses, however, is not irreversible as studies employing exclosures have illustrated. Areas of heavily grazed, graminoid dominated moorland when fenced to exclude sheep can revert back to *Calluna* dominance in as little as 6-10 years (Fenton, 1936; Hewson, 1977; Miles *et al.*, 1978; Rawes & Hobbs, 1979; Rawes, 1983).

The *Calluna* declines in the seven catchments studied all post-date the establishment of commercial sheep farming in Scotland and Ireland during the mid- to late-18th century (Fenton, 1980; Innes, 1983; O'Toole, 1985), and the major expansion in sheep numbers in North Wales during the 17th and 18th centuries (Hughes *et al.*, 1973). Whilst such a vague coincidence in timing is no basis on which to suggest a causal relationship between probable increased grazing pressures and *Calluna* loss it does at least suggest that grazing cannot be wholly discounted as a possible contributory factor.

It is clear, therefore, that with the available data it is impossible to state that grazing may have caused the vegetation changes experienced, despite the unequivocal evidence that sheep are capable of producing declines of heather and concomitant increase in graminoid species (Dalby *et al.*, 1971; Bakker, 1978; Anderson & Yalden, 1981). The circumstantial evidence, however, is strong and the possibility cannot be discounted. It seems likely that grazing by livestock may have made a considerable contribution to at least perpetuating the phenomenon of *Calluna* loss over extended periods of time in some areas, however, unequivocal evidence to support the aspersion that it may have been a primary cause of *Calluna* loss is at present lacking.

### 7.5 Conclusions

The data and analyses presented fail to fully and unequivocally elucidate the causes of the observed declines in *Calluna* cover at the sites studied. The best estimates of the possible causes of *Calluna* loss at the sites discussed above are summarised in Table 7.3.

Table 7.3: Summary of possible inferred causes of *Calluna* loss in the seven British and Irish catchments studied.

| | | Possible causes of the *Calluna* decline | | | |
|---|---|---|---|---|---|
| Site | Onset of *Calluna* decline (AD) | Fire | Little Ice Age | Pollution | Grazing |
| Round Loch of Glenhead | 1770 | Yes? | ? | ? | ? |
| Llyn Conwy | 1780 | Yes? | ? | ? | ? |
| Lough Muck | 1790 | No | ? | ? | ? |
| Loch Tanna | 1800 | No | ? | ? | ? |
| Loch Teanga | 1810 | No | ? | ? | ? |
| Blue Lough | 1890 | No | No | ? | ? |
| Loch Na Larach | 1900 | No | No | ? | ? |

The evidence presented and discussed suggests that in some instances high levels of burning may adversely affect the relative proportions of *Calluna* and grass cover in upland moorland catchments, and that in some UK and Irish regions increased burning of moorland vegetation may have been an important factor in promoting the decline of *Calluna vulgaris* over recent centuries. Fire activity in the Round Loch of Glenhead and Llyn Conwy catchments was found to be significantly statistically related to the *Calluna* decline, suggesting a possible causal link. However, it is also clear that in other areas in which *Calluna* has declined equally markedly over the same period increased fire activity would not appear to have been a major contributory factor or primarily responsible.

Of the alternative hypotheses considered as possible causes contributing to declining *Calluna* cover, the available evidence suggests that increased grazing pressures associated with the intensification of commercial sheep farming in the uplands, may have been the most important, both as a factor compounding the effects of fire in intensively burned catchments and possibly as primary cause of *Calluna* loss in some areas.

The effects of grazing and burning may also have been compounded by other processes and environmental factors. Atmospheric pollutants, principally sulphur and nitrogen, may have destabilised plant communities sufficiently to make them increasingly susceptible in particular to grazing (Sydes & Miller, 1988). *Calluna* also has a reduced tolerance to grazing with increasing age (Grant *et al.*, 1981), and the continued demise of *Calluna* in recent decades may in part be due to a decreased frequency and quality of muirburn on many moors. Reduced staffing levels on upland estates (Phillips *et al.*, 1981; Sydes & Miller, 1988) have led to greater areas of Britain's moorlands becoming covered by leggy, mature heather which has been increasing heavily grazed and only infrequently burned (Hester & Sydes, 1992). Such areas of moorland are particularly susceptible to degradation and invasion by grasses (Miles, 1988).

Additional work is needed to further elucidate the relative importance of possible factors responsible for causing *Calluna* loss on a national scale. The issue of *Calluna* loss and the determination of its causes has been shown to be potentially complex, the work presented here at least clarifies this point. No single causative agent or process would appear to have been responsible for causing the observed national decline in *Calluna* cover, *i.e.* in some instances fire activity may be important whilst in others it may not. This work also provides a methodology of both palaeoecological techniques and robust statistical analyses for testing the wider hypotheses necessary to further elucidate the issue.

A similar methodology could be used to determine the relative importance of atmospheric pollution as a possible cause of *Calluna* loss, and at sites with satisfactory chronological control and climatic records the effects of climatic change. Determining the possible role of grazing, however, is much more potentially problematic. Direct evidence of grazing pressures is not obtainable from sedimentary sequences and cannot be reconstructed from historical documentary sources, at least not with the necessary degree of accuracy for statistical analyses (Hughes *et al.*, 1973; Sydes & Miller, 1988).

# Chapter 8: Conclusions

## 8.1 Microscopic charcoal analyses of moorland soils

The analyses of microscopic charcoal in moorland soil cores conducted in this study represent not only an assessment of the practicability of obtaining sufficiently well resolved fire histories from a potentially problematic sediment medium, but also an unique attempt to validate the fundamental principles of microscopic charcoal analysis. The reconstruction of fire histories using microscopic charcoal analyses of locations known to have been burned on specific dates in the past (determined using aerial photograph analyses) allowed a direct assessment of the effectiveness and accuracy of the charcoal analysis techniques at identifying and characterising charcoal assemblages deposited by local fires. Few former studies have sought to identify the form of fossil charcoal assemblages in such a direct manner.

The main conclusions drawn from this work are as follows:

- Analyses of aerial photographs represent an effective means of reconstructing temporal and spatial patterns of muirburn on moorland over the post-1940/50 period. GIS technology provides the most effectual means of analysing spatial information from aerial photographs for this period of time.
- Microscopic charcoal analyses of moorland soil cores can be used to reconstruct extended fire histories over time-scales of at least several centuries provided suitable soil deposits are available. The frequency and periodicity of burning for given locations on a moor can be reconstructed from the fossil microscopic charcoal record within the soil.
- Charcoal assemblages produced by *in situ* fires can be distinguished from those produced by nearby *ex situ* fires on the basis of their particle size class distributions.
- The spherical carbonaceous particle (SCP) record in moorland soil cores can provide a valuable isochrone for the relative dating of short soil profiles.

## 8.2 Taphonomy of microscopic charcoal in moorland contexts

The studies of microscopic charcoal taphonomy from muirburns produced a number of results which have implications for the interpretation of moorland fire histories, and possibly wider implications for the study of microscopic charcoal in other environments. The following points represent the main conclusions of the taphonomy studies:

- Moorland fires do not produce microscopic charcoal of different sizes in equal proportions. Smaller charcoal particles appear to be produced in significantly greater quantities than progressively larger ones. Such inequalities in the relative proportions of charcoal particles produced ('Production bias') have important implications for the interpretation of sediment charcoal assemblages, especially when charcoal particles are quantified on the basis of their size and the particle size structure of an assemblage is used to infer proximity to the source fire .
- The vast majority of microscopic charcoal particles produced by small-scale moorland fires appear to be deposited no further than approximately 70-80 m from the parent fire. Charcoal source areas for sediment sinks such as lakes in moorland catchments are, therefore, expected to be relatively small.
- The dispersal of microscopic charcoal particles from small-scale moorland fires is influenced greatly by the wind direction at the time of the fire. The vast majority of charcoal produced is dispersed down-wind of the parent fire, little is deposited laterally or into the wind.

## 8.3 The possible role of fire in the initiation of peat erosion

The palaeoecological approach adopted to determine whether changing fire regimes in seven upland lake catchments in the UK and Ireland could have been responsible for causing peat erosion proved effective. The main conclusions are outlined below:

- At only one of the seven sites studied, Blue Lough (Co. Donegal, Ireland), is it possible to suggest that moorland burning may have played an important role in initiating catchment peat erosion. Other factors such as climatic deterioration, atmospheric pollution and livestock grazing may also have contributed to the initiation and maintenance of erosion, however, this remains to be formerly tested.

- At the other six UK sites studied, Lough Muck, Llyn Conwy, Loch Na Larach, Round Loch of Glenhead, Loch Tanna and Loch Teanga, enhanced fire activity was not found to be significantly statistically related to peat erosion episodes and thus is not believed to have been a likely cause of erosion initiation. It is hypothesised that harsh climatic conditions during the Little Ice Age (*c.*1550-1850 AD; Lamb, 1982; Grove, 1988) represent the most likely cause of peat erosion in these catchments, however, such a hypothesis needs much more rigorous testing.

### 8.4 The possible role of fire in the initiation of the *Calluna* decline

A palaeoecological hypothesis testing approach was adopted to determine whether fire activity in seven UK and Irish lake catchments could have been responsible for causing the long-term declines in *Calluna vulgaris* cover experienced in each of them over the past 100-250 years. The conclusions of this work are noted below:

- At Llyn Conwy (North Wales) and Round Loch of Glenhead (Galloway, Scotland) the significant statistical relationships between the reconstructed fire activity and *Calluna* loss indices suggest that increased burning of catchment vegetation may have been a factor responsible for promoting the decline of heather cover. Grazing by livestock, particularly sheep, may also have been an additional contributory factor though this hypothesis remains to be further explored.
- At Blue Lough, Lough Muck, Loch Na Larach, Loch Tanna and Loch Teanga the onset of the *Calluna* decline was not associated with enhanced fire activity. The most likely cause of *Calluna* loss and the subsequent expansion of grasses is hypothesised to be overgrazing by livestock, primarily sheep. This hypothesis, however, needs more rigorous testing

### 8.5 Suggestions for further research

#### 8.5.1 Microscopic charcoal taphonomy

It is evident from reviewing the microscopic charcoal taphonomy literature that the subject is relatively poorly understood, and that further experimental work is needed to improve understanding in this crucial area. The main issues that need addressing, in my view, include:

- Determining the relative importance of atmospheric and streamborne inputs of microscopic charcoal to lake sediments. An issue which has received some study but which has not been resolved.
- Determining approximate distances over which microscopic charcoal particles of different sizes may be the dispersed from biomass fires, allowing effective delimitation of 'source areas' for sediment sinks. Existing theory of charcoal particle dispersal has little direct experimental basis, having been developed to a large degree around theories of particulates other than microscopic charcoal.
- An assessment of the effects of differential deposition and focusing of microscopic charcoal particulates in lake basins, information which could have a potentially profound influence upon the form of charcoal records in lake sediment sequences and thus their interpretation.

The work carried out in this study raises a number of issues concerning charcoal production and dispersal which require additional study in both moorland and wider contexts. Further work is needed to ascertain the extent to which biomass fires produce differential quantities of charcoal particulates of varying size. Are smaller particles produced in much greater quantities than progressively larger ones?, as suggested by the work on Tulach Hill, and if so what are the implications of such processes for interpreting charcoal assemblages from sediment profiles.

### 8.5.2 Microscopic charcoal analysis of moorland soils

Microscopic charcoal analyses of soil profiles have been greatly neglected in comparison with analyses of peat and lacustrine sediments, due perhaps to the problems encountered by palynologists working with soils (Dimbleby, 1961, 1985). The analyses of microscopic charcoal in mor humus moorland soils conducted in this study, however, provide a potentially useful technique for reconstructing extended local fire histories. Much further work is needed, however, to refine and develop such analyses to their full potential.

Possible future work in this field could further the characterisation of charcoal assemblages formed by *in situ* fires from those produced by nearby *ex situ* fires using their particle size distributions. Assessment of the applicability of fine resolution microscopic charcoal analyses to other soil systems is also required.

### 8.5.3 Palaeoecological investigations into the possible causes of peat erosion and *Calluna* loss

Peat erosion and *Calluna* loss are widespread phenomena in UK and Irish moorland areas and may have been for centuries or even millennia. In this thesis seven sites were studied in an attempt to determine whether excessive burning of moorland vegetation may have been responsible for causing erosion of catchment peat and declines in *Calluna* cover. The results suggest that increased fire activity may have been important in causing erosion and *Calluna* loss in a small number of the catchments studied. In order to assess the influence of possible alternative causes of peat erosion and *Calluna* loss, namely climatic change, atmospheric pollution and over-grazing by livestock, further analyses are required. The palaeoecological and statistical approach adopted to determine the effect of fire activity could be adapted to provide a relatively rigorous test of the alternative hypotheses.

An assessment of the causes of peat erosion and *Calluna* loss by these methods at a greater number of sites would be advantageous to determine whether regional patterns in the causes of these phenomena exist. A range of environmental gradients, *e.g.* climatic, altitudinal and atmospheric pollution load, could be assessed and may provide valuable information concerning possible causes and agents of environmental change in moorland environments.

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**Appendix 1**: Table summarising the methods of charcoal quantification used by a selection of palaeoecological studies.

| Authors & Date | Sites & Sediment type | Charcoal Method Used | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Iversen, J (1941) | 5/6 *bog* sites, Denmark<br>Peat | Pollen slide | Absolute abundance | Palynological study of vegetation history | 10000 BP |
| Davis, RB (1967) | Long Pond, Little Ossipee Lake, Eagle Lake & Bracey Pond, Maine | Pollen slide, particles >50 $\mu m$ length, produced reference slides of charcoal to prevent mis-identification | No./unit vol sed | Palynological study of vegetation history | 800 BP |
| Tsudaka, M & Deevey, ES (1967) | 4 lakes, S Maya area, Guatemala & El Salvador<br>Lake | Pollen slide | No./g dwt sed | Palynological study of vegetation history | 3000 BP |
| Iversen, J (1969) | Draved Forest, SW Jutland, Denmark<br>Mor humus | Pollen slide | Absolute abundance | Palynological study of vegetation history | 10000 BP |
| Waddington, JCB (1969) | Rutz Lake, Minnesota, USA<br>Lake | Pollen slide, 11 size classes | Charcoal area index (0-100) | Palynological study of vegetation history | 12000 BP |
| Bradbury, JP & Waddington, JCB (1973) | Shagawa Lake, NE Minnesota<br>Lake | Pollen slide, 3 size classes | Concentration ($mm^2/cm^3$) | Pollen & limnology study of veg & palaeolimnology | 2000 BP |
| Smith, DM, Griffin, JJ & Goldberg, ED (1973) | Pacific & Atlantic Oceans<br>Marine | Infrared spectroscopy | Elemental carbon content (Wt. %) | Influx of carbon from fossil fuel combustion | Surface sediments |
| Swain, AM (1973) | Lake of the Clouds, NW Minnesota, USA<br>Lake - laminated | Pollen slide, hot nitric acid treatment, 8 size classes | C:P ratio & area influx ($\mu m^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 1000 BP |
| Singh, G, Joshi, RD, Chopra, SK & Singh, AB (1974) | 5 lake sites, Rajasthan Desert, India | Pollen slide, particles 10-100 mm, individual sizing of particles | No./100 fields of view | Palynological study of vegetation history | 10000 BP |
| Bradbury, JP, Tarapchak, SJ, Waddington, JCB & Wright, RF (1975) | Meander Lake & Dogfish Lake, NE Minnesota<br>Lake | Pollen slide (unexplained) | No./ml | Palaeolimnology changes with respect to fire | 9000 BP |
| Griffin, JJ & Goldberg, ED (1975) | Santa Barbara Basin, California<br>Marine | Chemical digestion-infrared assay | % elemental carbon | Deposition & transport of charcoal in marine sediments | 1800 - 1970 AD |
| Tallis, JH (1975) | Lady Clough Moor, Yorkshire<br>Peat | Pollen slide, subjective 5-point scale & chemical digestion method | 5-point scale & % of dwt | Palynological study of vegetation history | 8000 BP |
| Hope, GS & Peterson, JA (1976) | Ijomba *mire*, Kemabu Plateau, New Guinea<br>Peat | Pollen slide (unexplained) | % of Total Pollen Sum | Palynological study of vegetation history | 14000 BP |
| Byrne, M, Michaelsen, J & Soutar, A (1977) | Santa Barbara Channel<br>Marine - laminated | Pollen slide, area of individual particles measured | Area influx ($mm^2/cm^2$) | Charcoal fire history compared to recent documented evidence | 1931 - 1971 AD |
| Mehringer, PJ, Arno, SF & Peterson, KL (1977) | Lost Trail Pass Bog, Montana, USA<br>Peat | Pollen slide, 8 size classes | No. <25 mm/ $cm^3$ & No. > 25 mm/ $cm^3$ | Palynological study of vegetation history | 12000 BP |

# Appendix 1: continued

| Authors & Date | Sites & Sediment type | Charcoal Method Used | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Cwynar, LC (1978) | Greenleaf Lake, Ontario, Canada<br>Lake - laminated | Pollen slide, 5 size classes | Area influx ($mm^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 770 - 1270 AD |
| Swain, AM (1978) | Hell's Kitchen Lake, NC Wisconsin, USA<br>Lake - laminated | Pollen slide, 6 size classes | C:P ratio & area influx ($\mu m^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 2000 BP |
| Tolonen, M (1978) | Lake Ahvenainen, S Finland<br>Lake - laminated | Pollen slide, 3 size classes | Area influx ($\mu m^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 7000 BP |
| Amundson, DC & Wright, HE (1979) | Kirchner Marsh, Wolf Creek & Lake of the Clouds<br>Lake and Peat | Pollen slide, 3 size classes | Concentration (No. & area/$cm^2$/yr), C:P ratio | Climate vs fire pollen study of veg change | 20000 BP |
| Davis, AM (1979) | Tamarack Creek, Wisconsin<br>Peat & fill | Pollen slide, size classes (not mentioned) | Area conc. ($mm^2/cm^3$) & area influx ($mm^2/yr^{-1}$) | Palynological study of vegetation history | 4500 BP |
| Edwards, KJ (1979) | Braeroddach Loch, Aberdeenshire<br>Lake | Pollen slide (unexplained) | No./ $cm^2$/yr | Human impact on vegetation | 9000 BP |
| Terasmae, J & Weeks, NC (1979) | Found, Perch & Boulter Lakes & Lac Louis, S Ontario, Canada<br>Lake | Pollen slide and gelatin-coated slides - counted under a microscope & by image analysing computer | % of Pollen Sum (unexplained) | Charcoal and pollen study of vegetation | 10000 BP |
| Head, L & Stuart, I-MF (1980) | Aire Basin, SW Victoria<br>Peat | Pollen slide, 2 size classes | No./$cm^3$ | Palynological study of vegetation history | 4500 BP |
| Hooley, AD, Southern, W & Kershaw, AP (1980) | Loch Sport & Hidden Swamps, SE Victoria, Australia<br>Peat | Pollen slide, particles >20 μm in length | No./$cm^3$ | Palynological study of vegetation history | 8000 BP |
| Huttunen, P (1980) | 1 bog & 3 lakes, Lammi, Finland<br>Peat & lake | Pollen slide, particles >20 μm in length | Influx (No./ $cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 9000 BP |
| Swain, AM (1980) | Hug Lake & Lake of the Clouds, NW Minnesota<br>Lake - laminated | Pollen slide, 8 size classes | C:P ratio & area influx ($\mu m^2/cm^3$) | Palynological study of vegetation history | 400 BP |
| Green, DG (1981) | Everitt Lake, Nova Scotia<br>Lake | Pollen slide, 3 size classes | Area influx ($cm^2/cm^{-2}/yr^{-1}$) | Model of fire effects on veg development | 11000 BP |
| Simmons, IG & Innes, JB (1981) | Bonfield Gill Head, North York Moors<br>Peat | Petri-dish - % estimation | % of total sample | Palynological study of vegetation history | 8000 BP |
| Singh, G (1981) | Lake Frome, S Australia<br>Lake | Pollen slide, particles >10 μm | No./$cm^3$ | Palynological study of vegetation history | 9500 BP |
| Tsudaka, M, Sugita, S & Hibbert, D (1981) | Mineral & Hall Lakes, NW America<br>Lake | Pollen slide, individual sizing | Area Influx ($\mu m^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 19000 BP |

## Appendix 1: continued

| Authors & Date | Sites & Sediment type | *Charcoal Method Used* | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Boyd, WE (1982) | Shewalton Moss, Ayshire, Scotland<br>Peat | Pollen slide, subjective 5-point scale | 5-point scale | Sub-surface charcoal formation | ? |
| Green, DG (1982) | Everitt Lake, Nova Scotia<br>Lake | Pollen slide, 3 size classes | Model of fire effects on veg development | Model of fire effects on veg development | 11000 BP |
| Sugita, S & Tsukada, M (1982) | Mineral & Hall Lakes, NW America<br>Lake | Pollen slide, individual sizing | Area Influx ($\mu m^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 19000 BP |
| Battson, RA & Cawker, KB (1983) | Mashagama Lake, Ontario, Canada<br>Lake | Pollen slide, counted 200 particles per slide in 9 size classes | % index (Ch. no./pollen sum + Ch. no.), No./gdwt, Area ($\mu m^2/g$) | Charcoal method/theory & palynological study of vegetation history | ? |
| Griffin, JJ & Goldberg, ED (1983) | Lake Michigan, USA<br>Lake | Chemical digestion-infrared assay | % elemental carbon | Inputs of carbon from fossil fuel combustion | 1923 - 1978 AD |
| Head, L (1983) | Boomer Swamp & Bridgewater Lagoon, SW Victoria, Australia<br>Peat & lake | Pollen slide point count after Clark (1982) | Area conc. ($mm^2/cm^2$) | Palynological study of vegetation history | 6500 BP |
| Head, L (1983) | Boomer Swamp, Long Swamp & Bridgewater Lagoon, SW Victoria, Australia<br>Peat & lake | Pollen slide point count after Clark (1982) | Area conc. ($mm^2/cm^3$) & C:P ratio | Palynological study of vegetation history | 7000 BP |
| Robinson, D (1983) | Machrie Moor, Arran<br>Peat | Pollen slide, (probably individual sizing) | Area conc. ($m^2/cm^3$) | Palynological study of vegetation history | 10000 BP |
| Tolonen, M (1983) | Salo, Pukkila, SW Finland<br>Peat | Pollen slide, subjective 5-point count | 5-point scale | Palynological study of vegetation history | 5500 BP |
| Whittington, G (1983) | Black Moss of Achnacree, Argyllshire<br>Podzolic palaeosol | Pollen slide, individual sizing | Units 20x20 $\mu m$ in size | Palynological study of vegetation history | 3500 BP |
| Heusser, CJ (1984+) | 5 sites, Fuego Patagonia, Chile<br>Peat | Pollen slide, particles 50-150 $\mu m$ in length | No./$cm^3$ | Fire history only - NO POLLEN | 11000 BP |
| Hickman, M, Schweger, CE & Habgood, T (1984) | Lake Wabamun, Alta, Canada<br>Lake | Pollen slide (unexpl) | Absolute abundance | Palynological study of vegetation history | 10000 BP |
| Hickman, M, Schweger, CE & Klarer, DM (1984) | Bapiste Lake, Alberta, Canada<br>Lake | Pollen slide (unexpl) | Absolute abundance | Palynological study of vegetation history | 4600 BP |
| Kothari, BK & Wahlen, M (1984) | Greenleaf Lake, NY, USA<br>Lake | Chemical digestion of organics & sieved out particles >38 $\mu m$ | Concentration (weight %) | Influx of carbon from fossil fuel combustion | 1580 - 1979 AD |
| Robinson, D (1984) | Machrie Moor, Arran, Scotland<br>Peat | 1) 7-point scale visual estimation of sieve washings; 2) Pollen slide, individual sizing; 3) Chemical digestion after Tallis (1975) | 7-point scale, % of dwt, & area conc. (($\mu m^2/cm^3$) | Comparison of charcoal methods | ? |

# Appendix 1: continued

| Authors & Date | Sites & Sediment type | Charcoal Method Used | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Winkler, MG (1984) | Several Wisconsin lake and bog sites | Theory of chemical digestion-ignition method | %/g dwt | | |
| Edwards, KJ (1985) | Lough Catherine, Co. Tyrone<br>Lake | Pollen slide (unexplained) | % of Total Pollen Sum | Human impact on vegetation | 8000 BP |
| Gajewski, K, Winkler, MG & Swain, AM (1985) | Ruby, Dark & Little Pine Lakes, NW Wisconsin<br>Lake | Pollen slide after Swain (1973), size classes not mentioned | Influx ($cm^2/cm^{-2}/yr^{-1}$), Conc. ($cm^2/cm^3$) & C:P ratio | Palynological study of vegetation history | 1000 BP |
| Macphail, MK & Colhoun, EA (1985) | Ooze Lake, SW Tasmania<br>Lake | Pollen slide (unexpl), particles >20 mm in length | No./$cm^3$ | Palynological study of vegetation history | 20000 BP |
| Singh, G & Geissler, EA (1985) | Lake George, NSW, Australia<br>Lake | Pollen slide point count | Surface area % per unit vol. of sediment | Palynological study of vegetation history | 750 000 BP |
| Tolonen, M (1985) | Palomaki, Paimio, SW Finland<br>Peat | Pollen slide, abundance & 4 size classes | C:P ratio & absolute abundance | Palynological study of vegetation history | 3000 BP |
| Winkler, MG (1985) | Duck Pond, Cape Cod, Massachusetts, USA<br>Lake | Chemical digestion-ignition method | %/gdwt & influx ($g/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 12000 BP |
| Anderson, RS, Davis, RB, Miller, NG & Stuckenrath, R (1986) | Upper Branch Pond, N. Maine<br>Lake | Pollen slide, 9 size classes (particles <180 mm), & 11 size classes of sieve washings (>180 mm) | Area | Palynological study of vegetation history | 15000 BP |
| Bradbury, JP (1986) | Meander Lake & Dogfish Lake, NE Minnesota<br>Lake | Pollen slide (unexplained) | No./$cm^3$ | Palynological study of vegetation history | 9000 BP |
| Clark, RL (1986) | Rotten Swamp, Australia<br>Peat | Pollen slide point count & point counts of mounted sediment slurries | Area concentration ($cm^2/cm^3$) & Area influx ($cm^2/cm^2/yr$) | Palynological study of vegetation history | 10000 BP |
| Dodson, JR (1986) | 3 sites/Breadalbane Basin & Wet Lagoon, SE Australia<br>Lake | Pollen slide point count after Clark (1982) | No./$cm^2$/yr | Palynological study of vegetation history | 15000 BP |
| Hirons, KR & Edwards, KJ (1986) | Lough Catherine, Weir's & Kilmaddy Loughs, Co. Tyrone<br>Lake | Pollen slide | % of Total Pollen Sum | Palynological study of Elm decline and related vegetation changes | 7500 BP |
| Kershaw, AP (1986) | Lynch's Crater, NE Australia<br>Lake | Pollen slide (unexplained) | No./$cm^3$ | Palynological study of vegetation history | 190000 BP |
| Winkler, MG, Swain, AM & Kutzbach, JE (1986) | Lake Mendota, SC Wisconsin, USA<br>Lake | Chemical digestion-ignition method | %/gdwt | Palynological study of vegetation history | 16500 BP |
| Ballantyne, CK & Whittington G (1987) | An Teallach, Wester Ross<br>Windblown sand | Pollen slide, units of 20x20 $\mu$m | No. of units 20x20 $\mu m$ | Origins & vegetation development of sand deposit | 8000 BP |
| Burney, DA (1987a) | L Kavitaha, Miangola Swamp & L. Tritrivakely, C Madagascar<br>Lake & Swamp | Chemical assay after Winkler (1985) & pollen slide, size class after Swain (1973), Graminoid vs 'other' charcoal | % of dry weight, influx ($mg/cm^{-2}/yr^{-1}$), area conc. ($mm^2/cm^{-3}$) | Palynological study of vegetation history | 36000 BP |

# Appendix 1: continued

| Authors & Date | Sites & Sediment type | Charcoal Method Used | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Burney, DA (1987b) | Lake Kavitaha, C Madagascar<br>Lake | Pollen slide, size classes after Swain (1973), Graminoid vs 'other' charcoal | Area influx ($mm^2/cm^2/yr^{-1}$) | Palynological study of vegetation history | 15000 BP |
| Clark, RL (1987) | Rotten Swamp, Australia<br>Peat | Pollen slide point count & point counts of mounted sediment slurries | Area conc. ($cm^2/cm^3$) & Area influx ($cm^2/cm^2/yr^{-1}$) | Palynological study of vegetation history | 10000 BP |
| Cwynar, LC (1987) | Kirk Lake, North Cascade Range, CanadaLake | Pollen slide after Waddington (1969), no mention of size classes | Area influx($mm^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 15000 BP |
| Dodson, JR & Bradshaw, RHW (1987) | Union Wood Lake & Slish Lake, Co. Sligo<br>Peat | Pollen slide point count after Clark (1982) | Point hits of charcoal (not converted to area) | Palynological study of vegetation history | 6600 BP |
| Robinson, D (1987) | Aukhorn Peat Mounds, Caithness, Scotland<br>Peat | Macrofossil & pollen slide size classes after Swain (1973) | Area conc. ($mm^2/cm^3$) & 7-point scale of abundance | Palynological study of vegetation history & peat mound formation | 8000 BP |
| Tolonen, M (1987a) | Oinilanmaki Mire, SW Finland<br>Peat | Pollen slide, abundance count | Absolute abundance | Palynological study of vegetation history | 4000 BP |
| Tolonen, M (1987b) | Lake Kankareenjarvi & Preitilansuo Bog, SW Finland<br>Lake and peat | Pollen slide, abundance and 4 size classes | No./1000 pollen & No./$cm^3$ | Palynological study of vegetation history | 8000 BP |
| Wein, RW, Burzynski, MP, Sreenivsa, BA & Tolonen, K (1987) | Depres Lake Bog & Regent Street Bog, New Brunswick, Canada<br>Peat | Pollen slide, 5 size classes | Area influx ($mm^2/g^{-1}/yr^{-1}$) | Vegetation study using pollen and charcoal | 3000 BP |
| Affleck, TL, Edwards, K & Clarke, A (1988) | Auchareoch, Arran<br>Peat | Pollen slide, particles >152 μm2 | Concentration (No./g) | Archaeological - pollen study | 8000 BP |
| Bohncke, SJP (1988) | Callanish area, Isle of Lewis<br>Peat | Pollen slide (unexpl) | Concentration (unexpl) | Palynological study of vegetation history | 8500 BP |
| Bussell, MR (1988) | L. Waiau swamp & Waverley Beach, Wanganui District, New Zealand<br>Peat | Pollen slide point count after Clark (1982) | Area ($mm^2/cm^{-3}$) | Palynological study of vegetation history | 7000 BP |
| Chambers, FM, Kelly, RS & Price, S-M (1988) | Moel y Gerddi mire, Gwynedd, N Wales<br>Peat | Pollen slide (unexpl) | Not mentioned | Palynological study of vegetation history | 9000 BP |
| Clark, JS (1988) | Deming Lake, NW Minnesota, USA<br>Lake - laminated | Petrographic thin sections, size classes | Area influx ($cm^2/cm^2/yr^{-1}$) | Theory behind thin section method, charcoal only | 1640 - 1985 BP |
| Dodson, JR, Enright, NJ & McLean, RF (1988) | 2 sites in Te Paki region, N Island, New Zealand<br>Peat | Pollen slide point count after Clark (1982) | Influx (no mention of No. or area) | Palynological study of vegetation history | 16500 BP |
| Edwards, KJ, Whittington, G & Hirons, KR (1988) | 4 peat deposits, S Uist<br>Peat | Pollen slide (unexplained) | Area influx($cm^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 12500 BP |

# Appendix 1: continued

| Authors & Date | Sites & Sediment type | Charcoal Method Used | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Enright, NJ, McLean, RF & Dodson, JR (1988) | Te Werahi & Ponaki wetlands, Te Paki region, NZ<br>Peat | Pollen slide point count after Clark (1982) | Influx (no mention of units) | Palynological study of vegetation history | 4000 BP |
| Kodela, PG & Dodson JR (1988) | South Salvation Creek Swamp, NSW, Australia<br>Peat | Pollen slide point count after Clark (1982) | Influx (No./ $cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 5500 BP |
| Kvamme, M (1988) | 4 peat sites, W Norway<br>Peat | Pollen slide (unexplained) | Absolute abundance & % of Total Pollen sum | Palynological study of vegetation history | 2000 BP |
| Newell, PJ (1988) | Sheshader, Isle of Lewis<br>Peat | Macrofossil | 6-point scale of abundance | Archaeological & palynological study of vegetation | 4000 BP |
| Nilssen, EJ (1988) | 4 sites, Lofoten Area, N Norway<br>Peats & soils | Pollen slide (unexplained) | % of Total Pollen Sum | Palynological study of vegetation history | 10000 BP |
| O'Connell, M, Molloy, K & Bowler, M (1988) | Several sites, Connemara, W Ireland<br>Lake & peat | Pollen slide, particles >37 mm in length | % of Total Terrestrial Pollen Sum | Palynological study of vegetation history | 11000 BP |
| Odgaard, BV (1988) | Several sites, W Jutland, Denmark<br>Peats & soils | Pollen slide point count after Clark (1982) | $mm^2$ as % of Total Pollen Sum | Palynological study of vegetation history | 10000 BP |
| Robinson, DE & Dickson, JH (1988) | Machrie Moor, Arran<br>Peat | Pollen slide size classes after Swain (1973) | Area conc. ($mm^2/cm^3$) | Palynological study of vegetation history | 10000 BP |
| Winkler, MG (1988) | Washburn & Hook Lake Bogs, SC Wisconsin, USA<br>Peat | Chemical digestion-ignition method | %/g dwt | Palynological study of vegetation history | 16000 BP |
| Clark, JS (1989) | Deming Lake, NW Minnesota<br>Lake - laminated | Petrographic thin section point count (after Clark, 1988) | Area influx ($cm^2/cm^{-2}/yr^{-1}$) | Ecological consequence of fire disturbance on veg | 1240 - 1960 AD |
| Clark, JS, Merkt, J & Muller, H (1989) | Schleinsee, W Germany<br>Lake - laminated | Petrographic thin sections, ? size classes ('5, 10, 15, ... square units') | Area influx ($mm^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 13500 BP |
| D'Costa, DM, Kershaw, AP & De Deckker, P (1989) | Main Lake & NW Crater Lake, Tower Hill, Victoria, Australia<br>Lake | Pollen slide, particles >10 μm length | No./ $cm^3$ | Palynological study of vegetation history | 12000 BP |
| Hannon, GA & Bradshaw, RHW (1989) | Oak Island & Birch Island, Connemara<br>Mor humus | Pollen slide point count after Clark (1982) | No./$cm^2/cm^3$ | Palynological study of vegetation history | 1000 BP |
| Heusser, CJ (1989) | Caleta Robalo, Tierra del Fuego<br>Peat | Pollen slide (unexplained) | Area influx ($mm^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 13000 BP |
| Macdonald, GM (1989) | Toboggan Lake, SW Alberta, Canada<br>Lake | Pollen slide point count after Clark (1982) | C:P ratio & area influx($mm^2/cm^{-2}/yr^{-1}$) | Palynological study of vegetation history | 10500 BP |

# Appendix 1: continued

| Authors & Date | Sites & Sediment type | Charcoal Method Used | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Bennett, KD, Simonson, WD & Peglar, SM (1990) | Hockham & Quidenham Meres, East Anglia<br>Lake | Pollen slide point count (Clark, 1982) | Area concentration ($cm^2/cm^3$), C:P ratio | Palynological study of vegetation history | 10000 BP |
| Bradshaw, RHW & Zackrisson, O (1990) | Penningholmen, N Sweden<br>Forest humus soils | Pollen slide & macrofossil (>160 mm) | Only macro presented (No./$cm^2/yr^{-1}$) | Palynological study of vegetation history | 3000 BP |
| Burrows, CJ & Russell, JB (1990) | Quagmire Tarn & Windy Tarn, Prospect Hill, NZ<br>Peat | Macrofossil - No quantification | Presence of visible charcoal layers | Palynological study of vegetation history | 12000 BP |
| Clark, JS (1990) | Deming, Budd & Arco Lakes<br>Lake | Petrographic thin section point count (after Clark, 1988) | Area influx($cm^2/cm^{-2}/yr^{-1}$) | Effects of fire and climate on veg development | 1200 - 1950 AD |
| Clark, JS (1990) | 10 forest stands, Itasca State Park, NW Minnesota<br>Forest soils | Petrographic thin section point count (after Clark, 1988) | Area influx($cm^2$/cm-2/$yr^{-1}$) | Model of effects of fire suppression on forestry | 1800 - 1950 AD |
| Dodson, JR (1990) | Lough Camclaun, Lough Adoon Valley & Hill Bogs, Co. Kerry<br>Lake & peat | Pollen slide point count after Clark (1982) | Area conc. ($cm^2/cm^3$ ) | Palynological study of vegetation history | 9500 BP |
| Edney, PA, Kershaw, AP & De Deckker, P (1990) | Lake Wangoom, SE Australia<br>Lake | Pollen slide, particles >10 mm | No./ $cm^3$ | Palynological study of vegetation history | 51000 BP |
| Hirons, KR (1990) | Kinloch, Rhum<br>Peat | Pollen slide, particles >169 $\mu m^2$, duplicate charcoal & pollen counts | No./$cm^3$ & % of Total Pollen Sum | Palynological study of vegetation history | 8000 BP |
| Hirons, KR & Edwards, KJ (1990) | Kinloch, Rhum<br>Peat | Pollen slide, particles >169 $\mu m^2$, duplicate charcoal & pollen counts | No./$cm^3$ & % of Total Pollen Sum | Palynological study of vegetation history | 8000 BP |
| Mitchell, FJG (1990) | 3 forest sites, Killarney, Ireland<br>Mor humus | Pollen slide point count after Clark (1982) | Area conc. ($cm^2/cm^3$ ) | Palynological study of vegetation history | 1000 BP |
| O'Connell, M (1990) | Bunnyconnellan, Co. Mayo, Ireland<br>Peat | Pollen slide, particles >37 $\mu m$ in length | % of Total Terrestrial Pollen Sum | Palynological study of vegetation history | 6000 BP |
| Tallis, JH & Switsur, VR (1990) | Robinson's Moss, S Pennines, England<br>Peat | Macrofossil and pollen slide, particles >20 $\mu m$ | No./$traverse^{-1}$ | Palynological study of vegetation history | 9000 BP |
| Edwards, KJ, Hirons, KR & Newell, PJ (1991) | Peat near Loch Dee, Galloway<br>Peat | Pollen slide, No. of particles | No./ $cm^3$ | Pollen studies of minerogenic layers in peat | 5500 BP |
| Jacobson, GL, Almquist-Jacobson, H & winne, JC (1991) | Crystal Fen, NC Maine<br>Peat | Pollen slide point count after Clark (1982) | C:P ratio | Palynological study of vegetation history & Vegetation conservation | 1750 AD |
| MacDonald, GM, Larsen, CPS, Szeicz, JM & Moser, KA (1991) | Rainbow Lakes region, Alberta, Canada<br>Lake | 1) Pollen slide, 3 size classes; 2) Automated image analysis of pollen slides; 3) Macrofossil, 5 size classes; 4) Chemical digestion-combustion method | C:P ratio, area influx ($\mu m^2/cm^{-2}/yr^{-1}$), elemental carbon %/gdwt) & $g/cm^{-2}/yr^{-1}$) | Charcoal method theory & Palynological study of vegetation history | 250 BP |

## Appendix 1: continued

| Authors & Date | Sites & Sediment type | Charcoal Method Used | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Molloy, K & O'Connell, M (1991) | Loch Sheeauns, Connemara, Ireland Lake & peat | Pollen slide, particles >37 μm in length | % of Total Terrestrial Pollen Sum | Palynological study of vegetation history | 9500 BP |
| Sarmaja-Korjonen, K (1991) | Slattmossen, S Finland Peat | 2 pollen slide methods - 1) particles >5 μm; 2) 7 size classes | % of total pollen sum, Char. no.:Arboreal pollen ratio, Char. area:Arboreal pollen ratio & conc. ($\mu m^2/g$) | Comparison of charcoal methods | ? |
| Szeicz, JM & MacDonald, GM (1991) | Decoy Lake, S Ontario, Canada Lake | Pollen slide digital image analysis | C:P ratio | Palynological study of vegetation history | 12000 BP |
| Vuorela, I & Hiekkanen, M (1991) | Porvoo, S Finland Mineral soil | Pollen slide, estimate of % charcoal in organic matrix | % Charcoal/Matrix | Palynological study of vegetation history | 350 BP |
| Whittington, G, Edwards, KJ & Caseldine, CJ (1991) | Pickletillem Mire, NE Fife Peat | Pollen slide, units of 20x20 μm | Units of 20x20 μm/g wet wt | Palynological study of vegetation history | >11300 BP |
| Whittington, G, Edwards, KJ & Cundill, PR (1991) | Black Loch, N Fife Lake | Pollen slide, units of 20x20 μm | units of 20x20 μm/500 land pollen & units of 20x20 $\mu m/cm^3$ | Palynological study of vegetation history | 6000 BP |
| Alm, J, Tolonen, K & Vasander, H (1992) | Lakkasuo mire, Finland Peat | Macrofossil - No quantification | Presence of visible charcoal layers | Dated charcoal - Calculation of peat accumulation | 1500 BP |
| Bennett, KD, Boreham, S, Sharp, MJ & Switsur, VR (1992) | Dallican Water, Shetland Lake | Pollen slide point count (Clark, 1982) | Area concentration (cm2/cm3) | Palynological study of vegetation history | 10000 BP |
| Bennett, KD, Fossitt, JA, Sharp, MJ & Switsur, VR (1992) | Loch Lang, S. Uist Lake | Pollen slide point count (Clark, 1982) | Area concentration ($cm^2/cm^3$) | Palynological study of vegetation history | 11000 BP |
| Blackford, JJ, Edwards, KJ, Dugmore, AJ, Cook, GT & Buckland, PC (1992) | Altnabreac & Loch Leir, NE Scotland Peat | Pollen slide (unexpl), particles >10 mm | Concentration (No./ pollen grain) | Pine decline & volcanic ash? | 10000 BP |
| Bradshaw, RHW & Hannon, G (1992) | Fiby Forest, Sweden Forest humus soils | Pollen slide & macrofossil (>160 mm) | Only macro presented ($No./cm^2/yr^{-1}$) | Palynological study of vegetation history | 2000 BP |
| Charman, DJ (1992) | Cross Lochs, Sutherland Peat | Macrofossil, 2 size classes (125-500 & >500 mm length), 5-point scale | 5-point scale | Blanket mire formation | 10000 BP |
| Kolstrup, E (1992) | 4 glacial sections, Jutland, Denmark Sands & organics | Pollen slide (unexpl), particles >10 $\mu m^2$ | Absolute abundance | Palynological study of vegetation history | 60000 BP |
| Ladd, PG, Orchiston, DW & Joyce, EB (1992) | Killiecrankie & Middle Patriarch Swamps, Flinders Island, Australia Peat | Pollen slide methods - (1) particles >20 mm, (2) point count after Clark (1982) | Absolute abundance & $mm^2/g$ | Palynological study of vegetation history | 10100 BP |
| Odgaard, BV (1992) | Lakes Solso & Skanso, Denmark Lake | Pollen slide point count after Clark (1982) | Conc. (mm2/cm3 wet sed) | Models charcoal and pollen influx to lake sediment | 6000 BP |

# Appendix 1: continued

| Authors & Date | Sites & Sediment type | Charcoal Method Used | Charcoal expression | Aims of study | Time scale |
|---|---|---|---|---|---|
| Sarmaja-Korjonen, K (1992) | 4 small lakes, S Finland<br>Lake | Pollen slide, 7 size classes | Conc. ($\mu m^2$/g) & C:Arboreal pollen *ratio* | Palynological study of vegetation history | 8000 BP |
| Bradshaw, RHW (1993) | Penningholmen, *Fiby* & Lake Malaren, Sweden<br>Forest humus soils | Macrofossil (>160 μm) | No./ $cm^3$ | Palynological study of vegetation history | 2000 BP |
| Day, P (1993) | Star Carr, Yorkshire<br>Peat | Pollen slide point count after Clark (1982) | Area / g dwt | Palynological study of vegetation history | 10000 BP |
| Foster, DR & Zebryk, TM (1993) | Black Gum Swamp & Hemlock Hollow, Massachusetts<br>Peat | Pollen slide point count after Clark (1982), only particles >15 μm in length counted | C:P ratio | Palynological study of vegetation history | 13000 BP |
| Gell, PA, Stuart, I-M & Smith, JD (1993) | Tea Tree Swamp, Victoria, Australia<br>Peat | Pollen slide point count after Clark (1982) of sediment slurry | C:Eucalyptus pollen conc. ratio | Palynological study of vegetation history | 3000 BP |
| Hall, VA, Pilcher, JR & McCormac (1993) | Sluggan, Fallahogy & Ballyscullion Bogs, N Ireland<br>Peat | Pollen slide, particles 10-80 μm | % of Total Pollen Sum | Palynological study of vegetation history | 750 - 1150 AD |
| Mighall, T & Chambers, FM (1993) | Copa hill, Cwmystwyth, Wales<br>Peat | Pollen slide point count after Clark (1982) | Area conc. ($mm^2/mm^3$) | Palynological study of vegetation history | 4000 BP |
| Motzkin, G, Patterson, WA & Drake, NER (1993) | Marconi Atlantic White Cedar Swamp, Cape Cod, Massachusetts, USA<br>Peat | Pollen slide (unexpl) | C:P ratio | Palynological study of vegetation history | 1500 BP |
| Peglar, SM (1993) | Diss Mere, Norfolk, UK<br>Lake - laminated | Pollen slide, particles >5 μm in length, macrofossil | Influx (No./ $cm^{-2}/yr^{-1}$) & % of Total Pollen Sum | Elm decline pollen study | 250 yrs (c.5000 BP) |
| Peglar, SM (1993) | Diss Mere, Norfolk, UK<br>Lake - laminated | Pollen slide, particles >5 μm in length, macrofossil | Influx (No./ $cm^{-2}/yr^{-1}$) & % of Total Pollen Sum | Palynological study of vegetation history | 7000 BP |
| Tipping, R, Edmonds, M & Sheridan, A (1993) | *Creag na Caillich*, Killin, Perthshire, Scotland<br>Peat | Pollen slide, 4 size classes | % of TLP, No./500 land pollen, & Conc. (No./cc) | Charcoal and Palynological study of vegetation history | 6500 BP |
| Whittington, G & Edwards, KJ (1993) | Biggings Field & Loch of Biggins, Papa Stour, Shetland<br>Mineral soil & lake | Pollen slide, units of 20x20 μm | Units of 20x20 μm | Palynological study of vegetation history | 5000 BP |
| Aucour, A-M & Hillaire-Marcel, C (1994) | Kashiru bog, Burundi<br>Peat | Macrofossil (>125 μm) | % of macrofossils >125 μm | C3 vs C4 plants - climate implications | 40000 BP |
| Burney, DA, Pigott Burney, L & MacPhee, RDE (1994) | Laguna Toruguero, Puerto Rico<br>Lake | Pollen slide, 8 size classes, Graminoid vs 'other' charcoal | Area ($mm^2/cm^{-3}$) | Fire history from charcoal only - NO POLLEN | 6000 BP |
| Martin, ARH (1994) | Kurnell Fen, E Australia<br>Peat | Pollen slide, particles >120 μm in length | % of Dry Land Pollen Sum | Palynological study of vegetation history | 10000 BP |
| Piperno, DR (1994) | Lake Wodehouse, Panama<br>Lake | 'Phytolith' method, particles 5-50 μm | No. per 20 $cm^3$ sediment | Phytolith and charcoal study | 4000 BP |

**Appendix 2**: Table of charcoal size classes used in previous palaeoecological studies.

| Authors & Date | Sites | Charcoal Size Classes |
|---|---|---|
| Waddington, JCB (1969) | Rutz Lake, Minnesota, USA | **11** size classes (mean area ranging from 113 $\mu m^2$ ..to.. 6188 $\mu m^2$) |
| Bradbury, JP & Waddington, JCB (1973) | Shagawa Lake, NE Minnesota | **3** size classes (<50, 50-400 & >400 $\mu m^2$ |
| Swain, AM (1973) | Lake of the Clouds, NW Minnesota, USA | **8** size classes (85-760 $\mu m^2$ ..to.. >5830 $\mu m^2$) |
| Mehringer, PJ, Arno, SF & Peterson, KL (1977) | Lost Trail Pass Bog, Montana, USA | **8** size classes (100-625 $\mu m^2$ ..to.. >30625 $\mu m^2$) |
| Cwynar, LC (1978) | Greenleaf Lake, Ontario, Canada | **5** size classes (58-289 $\mu m^2$ ..to.. >1733 $\mu m^2$) |
| Swain, AM (1978) | Hell's Kitchen Lake, NC Wisconsin, USA | **6** size classes (85-169 $\mu m^2$ ..to.. >845 $\mu m^2$) |
| Tolonen, M (1978) | Lake Ahvenainen, S Finland | **3** size classes (<50, 50-400 & >400 $\mu m^2$) |
| Amundson, DC & Wright, HE (1979) | Kirchner Marsh, Wolf Creek & Lake of the Clouds | **3** size classes (0.5-5, 5-20 & >20 x10-4 $mm^2$) |
| Davis, AM (1979) | Tamarack Creek, Wisconsin | **?** Size class number and dimensions not defined |
| Head, L & Stuart, I-MF (1980) | Aire Basin, SW Victoria Australia | **2** size classes (10-20 & >20 μm in length) |
| Swain, AM (1980) | Hug Lake & Lake of the Clouds, NW Minnesota | **8** size classes (85-760 $\mu m^2$ ..to.. >5830 $\mu m^2$) |
| Green, DG (1981) | Everitt Lake, Nova Scotia | **3** size classes (225-900, 900-3600 & >3600 $\mu m^2$) |
| Green, DG (1982) | Everitt Lake, Nova Scotia | **3** size classes (225-900, 900-3600 & >3600 $\mu m^2$) |
| Battson, RA & Cawker, KB (1983) | Mashagama Lake, Ontario, Canada | **9** size classes (100-199 $\mu m^2$ ..to.. >2000 $\mu m^2$) |
| Tolonen, M (1985) | Palomaki, Paimio, SW Finland | **4** size classes (50-100, 100-200, 200-400 & >400 $\mu m^2$) |
| Anderson, RS, Davis, RB, Miller, NG & Stuckenrath, R (1986) | Upper Branch Pond, N. Maine | **9** size classes (<180 μm in length) & **11** size classes of sieve washings (>180 μm) |
| Burney, DA (1987a) | L Kavitaha, Miangola Swamp & L. Tritrivakely, C Madagascar | **?** Size class number and dimensions not defined |
| Burney, DA (1987b) | Lake Kavitaha, C Madagascar | **?** Size class number and dimensions not defined |
| Cwynar, LC (1987) | Kirk Lake, North Cascade Range, Canada | **?** Size class number and dimensions not defined |
| Robinson, D (1987) | Aukhorn Peat Mounds, Caithness, Scotland | **?** Size class number and dimensions not defined |
| Tolonen, M (1987b) | Lake Kankareenjarvi & Preitilansuo Bog, SW Finland | **4** size classes (50-100, 100-200, 200-400 & >400 μm2) |

Appendix 2: continued

| Authors & Date | Sites | Charcoal Size Classes |
|---|---|---|
| Wein, RW, Burzynski, MP, Sreenivsa, BA & Tolonen, K (1987) | Depres Lake Bog & Regent Street Bog, New Brunswick, Canada | 5 size classes (100-2800, 2800-44400, 44400-135800, 135800-277200 & >277200 $\mu m^2$) |
| Clark, JS (1988) | Deming Lake, NW Minnesota, USA | ? Size classes (<442, 442-884, 884-1326 $\mu m^2$, ....) |
| Robinson, DE & Dickson, JH (1988) | Machrie Moor, Arran | ? Size class number and dimensions not defined |
| Clark, JS, Merkt, J & Muller, H (1989) | Schleinsee, W Germany | ? Size classes (<442, 442-884, 884-1326 $\mu m^2$, ....) |
| MacDonald, GM, Larsen, CPS, Szeicz, JM & Moser, KA (1991) | Rainbow Lakes region, Alberta, Canada | 3 pollen slide size classes (75-374, 375-2199 & >2199 $\mu m^2$) & 5 macrofossil size classes (2500-5300 µm2 ..to.. >40300 $\mu m^2$) |
| Sarmaja-Korjonen, K (1991) | Slattmossen, S Finland | 7 size classes (25, 65, 160, 225, 320, 450 & 450-3200 $\mu m^2$) |
| Charman, DJ (1992) | Cross Lochs, Sutherland | 2 macrofossil size classes (125-500 & >500 µm length) |
| Sarmaja-Korjonen, K (1992) | 4 small lakes, S Finland | 7 size classes (25, 65, 160, 225, 320, 450 & 450-3200 $\mu m^2$) |
| Tipping, R, Edmonds, M & Sheridan, A (1993) | Creag na Caillich, Killin, Perthshire, Scotland | 4 size classes (10-25, 26-50, 51-75 & >75 µm in length) |
| Burney, DA, Pigott Burney, L & MacPhee, RDE (1994) | Laguna Toruguero, Puerto Rico | 8 size classes (50-99, 100-199, 200-399, 400-799, 800-1599, 1600-3199, 3200-6399 & 6400-1279 $\mu m^2$) |

**Appendix 3**: Troels-Smith sediment descriptions of the mor humus soil cores from Tulach Hill and five additional Perthshire moorland sites.

The tables below contain sediment descriptions for all the soil cores used in this study. The sediments were described under a low-power binocular microscope using the method devised by Troels-Smith (1955).

**Sh** - Substantia humosa, completely disintegrated organic matter which has no apparent structure.
**Th** - Turfa herbacea or moss peat, formed predominantly from underground plant parts.
**Dg** - Detritus granosus, fragments of woody and herbaceous plants <2 mm but >0.1 mm in size, mainly above ground material.
**Dh** - Detritus herbosus, fragments of herbaceous plants >2 mm in size.
**Dl** - Detritus lignosus, fragments of wood and bark >2 mm in size.
**Ag** - Argilla granosa, mineral silt particles between 0.06 and 0.002 mm in size.
**Ga** - Grana arenosa, fine sand, particles between 0.06 and 0.6 mm in size.

The sediments presented are a mixtures of components, the Troels-Smith system estimates the relative abundance of components on a 5-point scale:

0 = absent
1 = up to 25%
2 = 25-50%
3 = 50-75%
4 = 100%
+ = a trace (<12.5%)

*Example*: Dg2 Dh1 Sh1 Dl+ Ag+, would represent a sediment sample composed of approximately 50% detritus granosus, 25% detritus herbosus, 25% substantia humosa, a trace of detritus lignosus and a trace of fine silt.

**Tulach 1**

| | |
|---|---|
| 0-8 mm | Moss & litter |
| 9-20 mm | Dg2 Dh1 Dl1 Sh+ |
| 21-24 mm | Dg2 Dh1 Sh1 Dl+ Ag+ |
| 25-30 mm | Sh2 Dg1 Ag1 Dh+ Dl+ |
| 31-76 mm | Sh2 Ag1 Ga1 Dh+ Dg+ |

**Tulach 2**

| | |
|---|---|
| 0-26 mm | Moss & litter |
| 27-28 mm | Tb3 Dg1 Dh+ |
| 29-32 mm | Dg2 Dh1 Dl1 Sh+ |
| 33-56 mm | Dg2 Sh2 Dh+ Dl+ |
| 57-74 mm | Dg2 Sh2 Dh+ Ag+ |

**Tulach 3**

| | |
|---|---|
| 0-4 mm | Moss & litter |
| 5-14 mm | Dg2 Dl1 Dh1 Ag+ |
| 15-24 mm | Dg2 Sh1 Dh1 Dl+ Ag+ |
| 25-36 mm | Dg2 Sh2 Dh+ Ag+ |
| 37-40 mm | Sh2 Dg1 Ag1 Dh+ Ga+ |
| 41-66 mm | Sh2 Ag1 Ga1 Dg+ Dh+ |

**Tulach 4**

| | |
|---|---|
| 0-5 mm | Moss & litter |
| 6-8 mm | Dg3 Dh1 Dl+ |
| 9-12 mm | Dg2 Sh1 Dh1 Dl+ |
| 13-18 mm | Dg2 Sh2 Dh+ Dl+ |
| 19-24 mm | Dg2 Sh2 Dh+ Dl+ Ag+ Ga+ |
| 25-64 mm | Sh2 Dg1 Ag1 Dh+ Ga+ |

## Appendix 3: continued

**Tulach 5**

| | |
|---|---|
| 0-5 mm | Moss & litter |
| 6-10 mm | Dg2 Dh1 Dl1 |
| 11-26 mm | Dg2 Dh1 Sh1 Dl+ |
| 27-30 mm | Dg2 Dh1 Sh1 Dl+ Ag+ |
| 31-36 mm | Dg2 Sh2 Dh+ Dl+ Ag+ |
| 37-66 mm | Sh2 Dg1 Ag1 Dh+ Dl+ |

**Tualch 6**

| | |
|---|---|
| 0-3 mm | Moss & litter |
| 4-10 mm | Dg2 Dl1 Sh1 |
| 11-12 mm | Sh2 Dg1 Dl1 |
| 13-20 mm | Sh3 Ag1 Dl+ Th+ Ga+ |
| 21-24 mm | Sh3 Ag1 Th+ Ga+ Dl+ |

**Tulach 7**

| | |
|---|---|
| 0-5 mm | Moss & litter |
| 6-13 mm | Dg2 Dh1 Dl1 Ag+ Sh+ |
| 14-17 mm | Dg2 Dh1 Sh1 Ag+ Dl+ |
| 18-21 mm | Sh2 Dg2 Ag+ Dl+ Dh+ |
| 22-29 mm | Sh3 Dg1 Ag+ Dl+ Dh+ Ga+ |

**Tulach 8**

| | |
|---|---|
| 0-8 mm | Moss & litter |
| 9-10 mm | Dg2 Dh2 Dl+ Sh+ |
| 11-15 mm | Dg2 Dh1 Hl1 Sh+ |
| 16-17 mm | Dg2 Dl1 Sh1 Dh+ Ag+ |
| 18-19 mm | Dg3 Dl1 Sh+ Dh+ Ag+ |
| 20-31 mm | Dg3 Sh1 Dl+ Dh+ Ag+ |

**Tulach 9**

| | |
|---|---|
| 0-15 mm | Moss & litter |
| 16-20 mm | Dh2 Dl2 Dg+ |
| 21-22 mm | Dh2 Dl1 Dg1 |
| 23-24 mm | Dg2 Dh1 Dl1 |
| 25-32 mm | Dg3 Dh1 Dl+ Sh+ |
| 33-34 mm | Dg3 Dh1 Dl+ Sh+ Ag+ |
| 35-44 | Dg3 Sh 1Dh+ Dl+ Ag+ |

**Tulach 10**

| | |
|---|---|
| 0-8 mm | Moss & litter |
| 9-28 mm | Dg2 Dl1 Dh1 |
| 29-34 mm | Dg3 Sh1 Dl+ Dh+ |

**Tulach 11**

| | |
|---|---|
| 0-8 mm | Moss & litter |
| 9-10 mm | Dg3 Dh1 Dl+ Sh+ |
| 11-18 mm | Dg3 Sh1 Dh+ Dl+ |
| 19-20 mm | Dg2 Sh2 Dh+ Dl+ Ag+ |
| 21-28 mm | Sh3 Dg1 Dh+ Dl+ Ag+ |

**Tulach 12**

| | |
|---|---|
| 0-9 mm | Moss & litter |
| 10-15 mm | Dg2 Sh1 Dh1 Dl+ |
| 16-21 mm | Dg2 Sh1 Dh1 Dl+ Ag+ |
| 22-27 mm | Sh2 Dg1 Ag1 Dh+ Dl+ Ga+ |
| 28-31 mm | Sh3 Ag1 Dh+ Dl+ Dg+ Ga+ |

**Tulach 13**

| | |
|---|---|
| 0-8 mm | Moss & litter |
| 9-15 mm | Dg2 Sh1 Dh1 Dl+ Ag+ Ga+ |
| 16-17 mm | Sh2 Dg1 Ag1 Ga+ Dh+ Dl+ |
| 18-21 mm | Sh2 Ag2 Ga+ Dg+ Dh+ Dl+ |
| 22-31 mm | Ag2 Sh1 Ga1 Dh+ |

**Tulach 14**

| | |
|---|---|
| 0-3 mm | Moss & litter |
| 4-9 mm | Dg2 Dl1 Dh1 |
| 10-17 mm | Dg2 Dh1 Sh1 Dl+ |
| 18-25 mm | Dg2 Sh2 Dh+ Dl+ Ag+ |
| 26-33 mm | Sh2 Dg1 Ag1 Dh+ Dl+ Ga+ |

**Tulach 15**

| | |
|---|---|
| 0-3 mm | Moss & litter |
| 4-5 mm | Dg2 Dh1 Dl1 Ag+ |
| 6-10 mm | Dg2 Dh1 Sh1 Dl+ Ag+ |
| 11-14 mm | Dg2 Sh1 Ag1 Dh+ Dl+ |
| 15-26 mm | Ag2 Dg1 Sh1 Dh+ Dl+ |

**Tulach 16**

| | |
|---|---|
| 0-5 mm | Moss & litter |
| 6-15 mm | Dg2 Dh1 Dl1 |
| 16-22 mm | Dg2 Dh1 Sh1 Dl+ |
| 23-34 mm | Dg2 Sh2 Dh+ Dl+ |

## Appendix 3: continued

**Gallow Hill**

| | |
|---|---|
| 0-5 | Tb3 Dl1 |
| 6-13 | Sh2 Dg1 Dl1 |
| 14-28 | Sh3 Dg1 Dl+ Th+ |
| 29-53 | Sh3 Dg1 Th+ |
| 54-57 | Sh3 Dg1 Th+ Ag+ |
| 58-65 | Sh3 Ag1 Th+ |
| 66-73 | Sh3 Ag1 Ga+ Th+ |
| 74-105 | Sh2 Ag2 Ga+ Th+ |
| 106-113 | Sh3 Ag1 Th+ |
| 114-120 | Sh3 Ag1 Ga+ Th+ |

**Happas Farm**

| | |
|---|---|
| 0-5 | Tb3 Dl1 |
| 6-15 | Sh2 Tl1 Ag1 |
| 16-21 | Sh3 Ag1 Th+ |
| 22-36 | Sh4 Ag+ Th+ |
| 37-50 | Sh3 Dg1 Ag+ |
| 51-63 | Sh2 Dg1 Ag1 Ga+ |
| 64-68 | Sh2 Ag1 Ga1 Dg+ |
| 69-84 | Sh2 Ag2 Ga+ Dg+ |

**Blacklaw Hill**

| | |
|---|---|
| 0-11 | Tb3 Dl1 |
| 12-27 | Sh2 Dg1 Dl1 Th+ |
| 28-35 | Sh3 Dg1 Ag+ |
| 36-121 | Sh3 Ag1 Dg+ |

**Trochry Hill**

| | |
|---|---|
| 0-10 | Tb3 Dg1 Tl+ |
| 11-50 | Dg2 Tl2 |
| 51-67 | Sh3 Dg1 Tl+ |
| 68-118 | Sh3 Dg1 |

**Auldallan Hill**

| | |
|---|---|
| 0-10 | Tb2 Tl2 |
| 11-14 | Sh2 Tl1 Th1 |
| 15-35 | Sh3 Tl1 Th+ |
| 36-90 | Sh3 Dg1 Tl+ Ag+ |

**Appendix 4:** The frequency and periodicity at which areas of vegetation on Tulach Hill, Blair Atholl, Perthshire were burned between 1940/50 and 1988.

| Approximate dates of burning (AP date) | Area of present vegetation ($m^2$) | No. of modern vegetation stands |
|---|---|---|
| '50 (1950) | 353,072 | 60 |
| '59 | 678,761 | 103 |
| '65 | 323,430 | 129 |
| '69 | 420,883 | 108 |
| '76 | 361,335 | 76 |
| '80 | 103,500 | 43 |
| '85 | 459,490 | 100 |
| '88 | 9,568 | 11 |
| '50,'59 | 240,717 | 35 |
| '50,'65 | 70,296 | 24 |
| '50,'69 | 24,128 | 26 |
| '50,'76 | 31,149 | 27 |
| '50,'80 | 15,362 | 10 |
| '50,'85 | 5,383 | 11 |
| '50,'88 | 1,651 | 6 |
| '59,'65 | 94,056 | 24 |
| '59,'69 | 84,303 | 29 |
| '59,'76 | 32,218 | 22 |
| '59,'80 | 12,143 | 10 |
| '59,'85 | 19,891 | 15 |
| '59,'88 | 1,833 | 6 |
| '65,'69 | 20,118 | 23 |
| '65,'76 | 28,421 | 24 |
| '65,'80 | 10,753 | 9 |
| '65,'85 | 94,742 | 34 |
| '65,'88 | 3,100 | 5 |
| '69,'76 | 64,675 | 39 |
| '69,'80 | 10,696 | 18 |
| '69,'85 | 171,249 | 63 |
| '69,'88 | 10,162 | 6 |
| '76,'80 | 13,060 | 4 |
| '76,'85 | 35,456 | 32 |
| '76,'88 | 347 | 3 |
| '80,'85 | 10,856 | 16 |
| '80,'88 | 1,495 | 2 |
| '85,'88 | 1,535 | 5 |
| '50,'59,'65 | 49,909 | 14 |
| '50,'59,'69 | 4,119 | 9 |
| '50,'59,'76 | 42,029 | 23 |
| '50,'59,'80 | 1,827 | 4 |
| '50,'59,'85 | 3,800 | 8 |

**Appendix 4**: continued

| Approximate date of burning (AP date) | Area of present vegetation ($m^2$) | No. of modern vegetation stands |
|---|---|---|
| '50,'59,'88 | 1,422 | 4 |
| '50,'65,'69 | 68 | 1 |
| '50,'65,'76 | 6,489 | 5 |
| '50,'65,'80 | 12,184 | 8 |
| '50,'65,'85 | 1,016 | 1 |
| '50,'65,'88 | 1,821 | 3 |
| '50,'69,'76 | 7,656 | 8 |
| '50,'69,'80 | 20 | 1 |
| '50,'69,'85 | 3,369 | 8 |
| '50,'69,'88 | 170 | 1 |
| '50,'76,'85 | 1,014 | 3 |
| '50,'76,'88 | 842 | 5 |
| '50,'80,'85 | 95 | 2 |
| '50,'80,'88 | 138 | 2 |
| '50,'85,'88 | 470 | 2 |
| '59,'65,'69 | 10,093 | 6 |
| '59,'65,'76 | 8,525 | 9 |
| '59,'65,'80 | 5,319 | 10 |
| '59,'65,'85 | 1,135 | 4 |
| '59,'65,'88 | 18 | 2 |
| '59,'69,'76 | 2,620 | 11 |
| '59,'69,'80 | 753 | 4 |
| '59,'69,'85 | 3,257 | 8 |
| '59,'69,'88 | 176 | 1 |
| '59,'76,'85 | 3,095 | 9 |
| '59,'76,'88 | 228 | 1 |
| '65,'69,'76 | 4,960 | 11 |
| '65,'69,'80 | 454 | 2 |
| '65,'69,'85 | 6,492 | 17 |
| '65,'76,'85 | 4,539 | 10 |
| '65,'76,'88 | 125 | 1 |
| '65,'80,'85 | 613 | 3 |
| '65,'80,'88 | 96 | 1 |
| '65,'85,'88 | 415 | 1 |
| '69,'76,'80 | 774 | 6 |
| '69,'76,'85 | 11,107 | 26 |
| '69,'76,'88 | 1,706 | 4 |
| '69,'80,'85 | 1,086 | 5 |
| '69,'80,'88 | 532 | 1 |
| '69,'85,'88 | 680 | 5 |
| '76,'80,'85 | 1,656 | 5 |

**Appendix 4**: continued

| Approximate date of burning (AP date) | Area of present vegetation (m²) | No. of modern vegetation stands |
|---|---|---|
| '76,'85,'88 | 845 | 4 |
| '80,'85,'88 | 551 | 1 |
| '50,'59,'65,'69 | 16 | 1 |
| '50,'59,'65,'76 | 12,011 | 5 |
| '50,'59,'65,'80 | 9,093 | 7 |
| '50,'59,'69,'76 | 2,939 | 8 |
| '50,'59,'69,'80 | 879 | 3 |
| '50,'59,'69,'85 | 1,579 | 4 |
| '50,'59,'76,'85 | 3,116 | 7 |
| '50,'59,'76,'88 | 2,550 | 3 |
| '50,'59,'85,'88 | 15 | 1 |
| '50,'65,'76,'88 | 336 | 3 |
| '50,'65,'80,'85 | 308 | 2 |
| '50,'65,'80,'88 | 22 | 1 |
| '50,'65,'85,'88 | 81 | 1 |
| '50,'69,'76,'80 | 5 | 1 |
| '50,'69,'76,'85 | 2,705 | 5 |
| '50,'69,'76,'88 | 1,257 | 2 |
| '50,'76,'85,'88 | 676 | 4 |
| '59,'65,'69,'76 | 4,218 | 2 |
| '59,'65,'69,'85 | 421 | 1 |
| '59,'65,'80,'85 | 129 | 1 |
| '59,'69,'76,'80 | 106 | 1 |
| '59,'69,'76,'85 | 695 | 4 |
| '59,'69,'80,'85 | 127 | 1 |
| '59,'76,'85,'88 | 19 | 1 |
| '65,'69,'76,'85 | 5,129 | 5 |
| '65,'76,'85,'88 | 18 | 1 |
| '69,'76,'80,'85 | 680 | 4 |
| '69,'76,'85,'88 | 391 | 2 |
| '69,'80,'85,'88 | 146 | 1 |
| '50,'59,'69,'76,'80 | 185 | 1 |
| '50,'59,'69,'76,'85 | 1,191 | 6 |
| '50,'59,'69,'76,'88 | 400 | 2 |
| '50,'59,'76,'85,'88 | 577 | 2 |
| '50,'65,'76,'85,'88 | 709 | 1 |
| '50,'69,'76,'85,'88 | 122 | 1 |
| '50,'59,'69,'76,'85,'88 | 100 | 1 |

# Appendix 5: $^{210}$Pb Chronologies

## Round Loch of Glenhead - $^{210}$Pb chronology (CRS Model)

| Depth (cm) | Date (AD) | Age (yr) | ± | Sedimentation rate (cm yr$^{-1}$) |
|---|---|---|---|---|
| 0.00 | 1985 | 0 | - | - |
| 1.25 | 1979 | 6 | 2 | 0.191 |
| 2.25 | 1974 | 11 | 2 | 0.179 |
| 3.25 | 1968 | 17 | 2 | 0.125 |
| 4.75 | 1955 | 30 | 3 | 0.112 |
| 6.50 | 1940 | 45 | 4 | 0.124 |
| 8.50 | 1922 | 63 | 7 | 0.146 |
| 10.50 | 1910 | 75 | 9 | 0.146 |
| 12.50 | 1898 | 87 | 12 | 0.146 |
| 14.50 | 1887 | 98 | 16 | ~0.196 |
| 18.50 | 1866 | 119 | 27 | ~0.196 |

Source Stevenson *et al.* (1990)

## Loch Teanga - $^{210}$Pb chronology (CRS Model)

| Depth (cm) | Date (AD) | Age (yr) | ± | Sedimentation rate (cm yr$^{-1}$) |
|---|---|---|---|---|
| 0 | 1987 | 0 | - | - |
| 2.00 | 1979 | 8 | 2 | 0.165 |
| 4.00 | 1966 | 21 | 2 | 0.143 |
| 6.00 | 1952 | 35 | 2 | 0.145 |
| 8.00 | 1938 | 49 | 3 | 0.150 |
| 10.00 | 1925 | 62 | 4 | 0.164 |
| 12.00 | 1912 | 75 | 6 | 0.157 |
| 14.00 | 1902 | 85 | 9 | 0.194 |
| 16.00 | 1891 | 96 | 10 | 0.194 |
| 18.00 | 1881 | 106 | 10 | 0.194 |
| 20.00 | 1870 | 117 | 11 | 0.194 |

## Appendix 5: continued

### Lough Muck - 210Pb chronology (CRS Model)

| Depth (cm) | Date (AD) | Age (yr) | ± | Sedimentation rate (cm $yr^{-1}$) |
|---|---|---|---|---|
| 0 | 1988 | 0 | - | - |
| 1.00 | 1984 | 4 | 2 | 0.276 |
| 3.00 | 1977 | 11 | 2 | 0.237 |
| 5.00 | 1966 | 22 | 2 | 0.164 |
| 7.00 | 1954 | 34 | 2 | 0.173 |
| 9.00 | 1943 | 45 | 2 | 0.206 |
| 11.00 | 1931 | 57 | 3 | 0.155 |
| 13.00 | 1917 | 71 | 3 | 0.125 |
| 17.00 | 1901 | 87 | 5 | 0.120 |
| 15.00 | 1885 | 103 | 8 | 0.120 |
| 19.00 | 1868 | 120 | 11 | 0.120 |
| 21.00 | 1851 | 137 | 14 | 0.120 |
| 23.00 | 1835 | 153 | 16 | 0.120 |

## Appendix 5: continued

**Blue Lough - $^{210}Pb$ chronology (CRS Model)**

| Depth (cm) | Date (AD) | Age (yr) | ± | Sedimentation rate (cm $yr^{-1}$) |
|---|---|---|---|---|
| 0 | 1988 | 0 | - | - |
| 0.50 | 1987 | 1 | 2 | 0.391 |
| 1.50 | 1985 | 3 | 2 | 0.323 |
| 2.50 | 1981 | 7 | 2 | 0.254 |
| 3.50 | 1976 | 12 | 2 | 0.195 |
| 4.50 | 1971 | 17 | 2 | 0.168 |
| 5.50 | 1965 | 23 | 2 | 0.145 |
| 6.50 | 1957 | 31 | 2 | 0.136 |
| 7.50 | 1950 | 38 | 3 | 0.133 |
| 8.50 | 1940 | 48 | 4 | 0.106 |
| 9.50 | 1930 | 58 | 4 | 0.079 |
| 10.50 | 1915 | 73 | 7 | 0.063 |
| 11.50 | 1900 | 88 | 11 | 0.063 |
| 12.50 | 1885 | 103 | 14 | 0.063 |

**Loch Tanna - $^{210}Pb$ chronology (CRS Model)**

| Depth (cm) | Date (AD) | Age (yr) | ± | Sedimentation rate ($cm\ yr^{-1}$) |
|---|---|---|---|---|
| 0 | 1986 | 0 | - | - |
| 0.5 | 1983 | 3 | 2 | 0.147 |
| 1.00 | 1979 | 7 | 2 | 0.128 |
| 1.50 | 1975 | 11 | 2 | 0.111 |
| 2.00 | 1970 | 16 | 2 | 0.110 |
| 2.50 | 1966 | 20 | 2 | 0.105 |
| 3.00 | 1961 | 25 | 2 | 0.101 |
| 3.50 | 1956 | 30 | 2 | 0.097 |
| 4.00 | 1950 | 36 | 2 | 0.088 |
| 4.50 | 1944 | 42 | 2 | 0.076 |
| 5.00 | 1938 | 48 | 3 | 0.079 |
| 5.50 | 1931 | 55 | 3 | 0.080 |
| 6.00 | 1924 | 62 | 3 | 0.063 |
| 6.50 | 1913 | 73 | 4 | 0.048 |
| 7.00 | 1898 | 88 | 6 | 0.036 |
| 7.50 | 1882 | 104 | 8 | 0.023 |

## Appendix 5: continued

### Llyn Conwy - $^{210}Pb$ chronology (CRS Model)

| Depth (cm) | Date (AD) | Age (yr) | ± | Sedimentation rate (cm $yr^{-1}$) |
|---|---|---|---|---|
| 0.00 | 1987 | 0 | - | - |
| 2.00 | 1980 | 7 | 2 | 0.247 |
| 4.00 | 1972 | 15 | 2 | 0.279 |
| 6.00 | 1965 | 22 | 2 | 0.288 |
| 8.00 | 1959 | 28 | 2 | 0.291 |
| 10.00 | 1952 | 35 | 2 | 0.345 |
| 12.00 | 1946 | 41 | 2 | 0.360 |
| 14.00 | 1941 | 46 | 3 | 0.370 |
| 16.00 | 1935 | 52 | 3 | 0.370 |
| 18.00 | 1929 | 58 | 3 | 0.355 |
| 20.00 | 1923 | 64 | 4 | 0.316 |
| 22.00 | 1916 | 71 | 4 | 0.276 |
| 24.00 | 1909 | 78 | 5 | 0.237 |
| 26.00 | 1900 | 87 | 6 | 0.212 |
| 28.00 | 1890 | 97 | 8 | 0.205 |
| 30.00 | 1880 | 107 | 10 | 0.205 |
| 32.00 | 1871 | 116 | 13 | 0.205 |
| 34.00 | 1861 | 126 | 17 | 0.205 |
| 36.00 | 1851 | 136 | 19 | 0.205 |
| 38.00 | 1842 | 145 | 20 | 0.205 |
| 40.00 | 1832 | 155 | 22 | 0.205 |

## **Appendix 6:** Round Loch of Glenhead - $^{14}C$ chronology

| Lab. No. | Depth (cm) | Uncalibrated date (BP) | Calibrated date BP at two sigma* |
|---|---|---|---|
| SRR-2180 | 37-42 | 2020±80 | 2289(**1985**)1820[1] |
| SRR-3258 | 42-47 | 1440±60 | 1494(**1329**)1280[1] |
| SRR-3259 | 48-53 | 1420±60 | 1410(**1313**)1270[1] |
| SRR-2811 | 53-58 | 1350±70 | 1384(**1287**)1160[1] |
| SRR-3260 | 61-66 | 730±60 | 740(**678**)566[1] |
| SRR-3261 | 68-73 | 1690±60 | 1730(**1602,1583,1579**)1500[1] |
| SRR-2812 | 75-80 | 1910±70 | 2039(**1868**)1700[1] |
| SRR-3262 | 82-87 | 2010±70 | 2129(**1959**)1840[1] |
| SRR-3263 | 89-94 | *1570±60* | *1600(**1503**)1340*[1] |
| SRR-2813 | 96-101 | 2550±70 | 2779(**2740**)2359 |
| SRR-3264 | 103-108 | 1810±60 | 1880(**1729**)1576[1] |
| SRR-3265 | 110-115 | 2720±60 | 2949(**2841,2831,2797**)2749[2] |
| SRR-2814 | 120-125 | 2250±70 | 2359(**2323**)2072[1] |
| SRR-2815 | 139-144 | 3970±70 | 4807(**4432**)4249[2] |
| SRR-2816 | 153-158 | 4660±70 | 5581(**5442,5429,5326**)5089[3] |
| SRR-2817 | 168-173 | 5180±80 | 6180(**5943**)5739[3] |
| SRR-2818 | 183-188 | 6390±80 | 7439(**7282**)7169[4] |
| SRR-2819 | 198-203 | 6890±70 | 7909(**7687**)7579[4] |
| SRR-2820 | 208-213 | 7250±70 | 8171(**8039**)7919[4] |
| SRR-2821 | 223-227 | 9280±80 | Too old for calibration |

* Dates calibrated to [1]Stuiver & Pearson (1986); [2]Pearson & Stuiver (1986); [3]Pearson *et al.* (1986); [4]Bidecadel weighted average of data from Linick *et al.*, (1985); Stuiver *et al.* (1986); Kromer *et al.* (1986) and Linick *et al.* (1986). Source Stevenson *et al.* (1990).

Source: Stevenson *et al.* (1990)