The Holocene history of *Pinus sylvestris* woodland in the Mar Lodge Estate, Cairngorms, Eastern Scotland

Danny Paterson

Institute of Natural Sciences, University of Stirling, Stirling, UK

Submitted for the degree of Doctor of Philosophy November 2011

Statement of Originality

I hereby confirm that this research was carried out by the undersigned and that all research material has been duly referenced and cited.

Danny Paterson, December 2010

Acknowledgements

This thesis has taken rather a long time to complete, there's a long list of people who've helped me, several of whom I've actually forgotten as they moved on or completed and left and I didn't. Thanks and apologies to all people with whom I've shared an office or lab space and have now vanished from my mind. Thanks for the company to those whose names I can still place, Helen Shaw, Sue Bowen, Althea Davies.

Throughout the three changes of departmental name: Department of Environmental Science, School of Biological and Environmental Sciences and now the Institute of Natural Sciences, help from laboratory, IT and cartographic staff, Helen Ewen, Scott Jackson, Bill Jamieson and John McArthur has been invaluable. Bob McCulloch helped with coring and together with Eileen Tisdall also provided guidance regarding pollen preparation and colorimetric analysis. Richard Tipping has provided excellent and cheerful supervision, and David Paterson very helpfully proof read the dissertation.

The NTS staff in Mar Lodge have also changed during the time I've been working on this project, but special thanks go to Peter Holden and Alister Clunas on the Estate and also to Shannon Fraser. Colin Edwards of Forestry Research has also been very helpful with aspects of pine ecology.

Lastly Shirley has waited (fairly) patiently as the project spent a long time apparently going nowhere, provided support when it seemed to be going into reverse and also proof read the whole thing. Thank you for that.

Abstract

This thesis investigates the past extent, structure and dynamics of Mar Lodge Caledonian pine (*Pinus sylvestris* L.) woodland, near Braemar in the south-eastern Cairngorms. The geographical extent and Holocene history of the Scottish pinewoods are generally understood, but the Mar pinewoods are relatively obscure. This thesis is concerned with the Holocene history of the Mar pinewoods; the timing and reasons for first appearance, the increase in abundance of *Pinus* to become a dominant species, the spatial extent of the woodland and its structure and form. The investigation includes changes to the woodland assemblage during its fragmentation and disappearance in the late Holocene and possible influences on the woodland from people living in the area.

At the heart of this thesis is an understanding of the factors underpinning the ecology of *Pinus* and the response of the species to competition with other taxa. This is related to the spatial and temporal changes in climate that contribute to the location and development of *Pinus* in Scotland and Mar Lodge. Areas comparable to Mar Lodge are defined as ‘core areas’ of pine woodland rather than ‘native areas’. This avoids the necessity of considering every short period of colonisation by *Pinus* in areas distal to large populations. The location, extent, form and behaviour of woodland according to macro sub-fossils and micro sub-fossils is used to define core woodland as those with a long presence of *Pinus*, often continuing to the present day. Areas with a long history but no extant population are regarded as peripheral areas.

This thesis consists of extensive palaeoecological investigations of three peat sequences: from within extant pine woodland (Doire Bhraghad), from just beyond its edge (White Bridge) and from peat with sub-fossil pine stumps located 10km west of the modern range of *Pinus* (Geldie Lodge). A range of techniques, including loss of mass on ignition and colorimetric light transmission analysis are applied to the peat, but palynological techniques form the basis of the investigation. Stomatal counts are used in

conjunction with pollen counts to explore the process of *Pinus* colonisation, and its increase in abundance to form woodland. *Pinus* percentage and influx, together with the ratio of arboreal to non-arboreal pollen and the percentage of *Empetrum* are used to define the density of the woodland canopy.

The stability of the Doire Bhraghad assemblage confirms the area as core *Pinus* woodland. *Pinus* is present from *c*. 9600 cal BP and dominates woodland from *c*. 9150 cal BP. Woodland here is a closed, solely *Pinus* canopy from *c*. 8600 until 4000 cal BP. Arrival of *Pinus* at Geldie Lodge is undated but occurs before *c*. 7550 cal BP. Woodland is always more open; *Pinus* is co-dominant with *Betula*, showing affinity with other peripheral areas. *Pinus* woodland fragments at all Mar Lodge sites from *c.* 3900 cal BP, disappearing from Geldie Lodge by *c.* 2800 cal BP and White Bridge by *c.* 1900 cal BP. Calluna replaces Pinus as the dominant species at all three sites. The disappearance of *Pinus* is thought to relate to regional climatic change toward wetter conditions.

At Geldie Lodge a prior Coleopteran study suggests *Pinus* growing on the mire surface to be small and short lived. These may not have been the only trees growing in the area but they perhaps contributed to the major fluctuations in arboreal and non-arboreal pollen. Early canopy fluctuations (*c*. 7550 to 6000 cal BP) at Geldie Lodge may be related to Mesolithic human activity; there is stronger evidence of human presence from *c*. 4000 cal BP, possibly including cereal cultivation. Evidence from Doire Bhraghad and White Bridge is indicative only of low intensity grazing activity. It is unlikely that human activity instigated the fragmentation and disappearance of woodland, but may have contributed to the process.

Contents

List of Figures

List of Tables

1 Thesis rationale and organisation

A great deal of attention has been paid to the past structure and extent of woodland in Scotland (Bennett 1984, Birks 1989, Tipping 1994, Huntley *et al* 1997), especially in relation to conservation ecology. Scottish woodland gives the greatest opportunities for re-wilding and woodland restoration in Britain and Caledonian pinewoods have formed a key section of palaeoecological studies aimed at informing this. The western woodlands of *Pinus sylvestris* in Torridon (Birks 1970; Pennington *et al* 1972), Inverpolly (Pennington *et al* 1972), Glen Affric (Davies 2003 a and b; Froyd 2005; Froyd and Bennett 2006; Shaw 2006), and Rannoch Moor (Ward *et al* 1987, Bridge *et al* 1990) have been thoroughly described. In the east attention has been focused on Speyside (Birks 1970; O'Sullivan 1974a, 1976; Pratt 2006a and b) on the western side of the Cairngorms.

The history and structure of the Mar woodlands in the eastern Cairngorms is largely untested. Studies by Pears (1968, 1970a) and Huntley (1994) were not specifically directed toward *Pinus* woodland. Pears (1968, 1970) investigated the *Pinus* tree-line in the Cairngorms, including the eastern Cairngorms, his investigation preceded the development of pollen techniques currently understood to reveal local woodland. Neither Pears nor Huntley (1994) aimed to investigate the nature and development of *Pinus* woodland in upper Deeside on the valley floor.

This thesis will investigate the Caledonian pinewoods of Mar, regarded as forming part of one of eight areas of naturally occurring woodland (*sensu* Steven and Carlisle 1959). The overarching aim of the thesis is to present a palaeoecological study, utilising recently developed techniques, to investigate the appearance and development of *Pinus* woodland in the Holocene in a relatively high altitude area toward the western edge of its Deeside range.

Chapter 2 sets out the parameters of this investigation. Section 2.3 addresses the question of the definition of ‘native woodland’ and the relationship between ‘native’ and areas in which *Pinus* woodland has a long history. These definitions are important in current conservation and management thinking and also provide a network of areas in Scotland with which to compare the development of the Mar pinewoods. This is preceded by an introduction to the ecology and preferred growth conditions of *Pinus sylvestris* (Section 2.2). Together with the methods used to describe the past behaviour and extent of *Pinus* woodland elsewhere in Scotland (Sections 2.4-2.7), this forms the basis by which the development of the Mar woodland is addressed in this thesis. Section 2.8 summarises this information and lists specific aims for the whole thesis.

The distinctive geography, geology, climate, ecology and human history of the Mar area is described in Section 3.1. This provides detail to the aspects of upper Deeside, which have affected the development of Mar woodland and helps to define the selection of sites (Section 3.2). Detailed description and justification of each investigated site is provided in Section 3.3. The chapter is completed with a description of the methods used to analyse each site.

Results, including sedimentary descriptions, pollen counts and chronological control of each site are followed by interpretation of all data and presented separately for each of the investigated sites (Chapter 4, 5 and 6). Chapter 7 compares the interpretation of the development of the sites in this study with each other and other areas of Scotland, using a chronological approach, following the aims set out here and in Section 2.8. Conclusions are presented in Chapter 8.

Figure 2.1 Looking east over the open woodland and scattered trees with *Calluna* of Glen Lui, Mar Lodge Estate. One of the sites in this study, Doire Bhraghad, is in the centre of the picture.

2 Defining the past presence and abundance of *Pinus* in Scotland: a review of the literature

2.1 Introduction

Although the species grows in many countries, in Scotland, *Pinus sylvestris* (*Pinus*) has become an iconic species (i.e. Scot's Pine). The association of the eastern pine woodlands with the British monarchy may have helped it to emerge as a symbol of national identity, and as a tourist attraction, with visitors to the area now numbering several tens of thousands each year. Thus the presence and identification of former presence of *Pinus* is of great interest and economic importance in connection with forest restoration and management in Scotland.

Ready identification of nearly all parts of the plant (Bennett 1984) should make documenting localities where *Pinus* once grew straightforward, but this is not always the case in practise, as this chapter shows (Section 2.4). The classic image of *Pinus* woodland is exemplified in Figure 2.1 but the actual former extent, abundance, appearance, structure, composition and the demise of *Pinus* woodland is subject to considerable, sometimes poorly informed, debate. Before past work defining these is evaluated (Section 2.4), the biological and edaphic requirements of *Pinus* are reviewed (Section 2.2). Section 2.3 considers how to define the areas that are of greatest relevance to the history of *Pinus* in the Mar Lodge area. Sites and areas of Scotland referred to in this and subsequent chapters are shown in Figure 2.2.

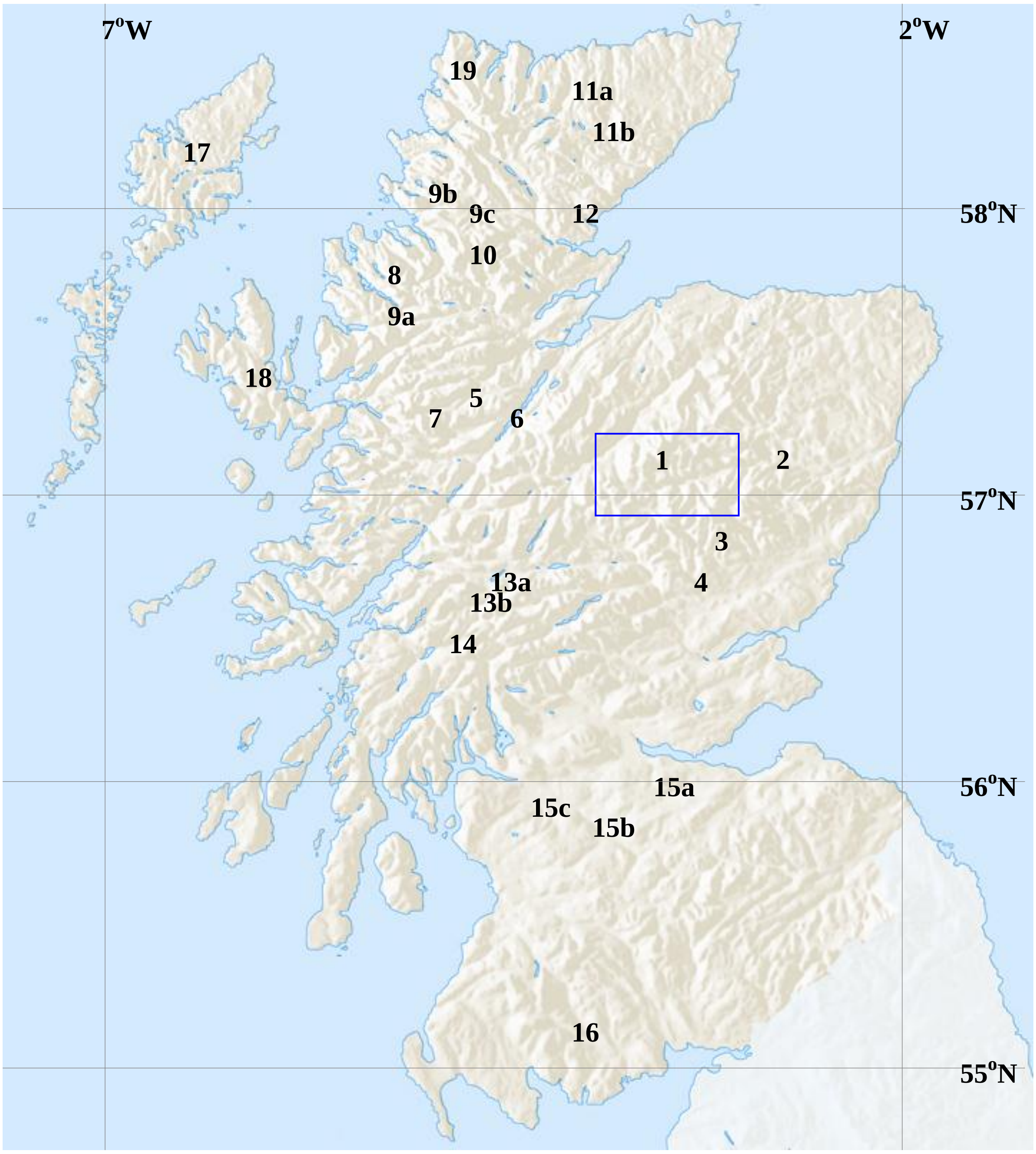


Figure 2.2 Mainland Scotland and the Western Isles, locations of sites referenced in text. (1) Speyside and the Cairngorms, sites within this area are located in Figure 3.1 and 3.4. (2) Howe of Cromar, Braeroddach Loch and Loch Davan, Edwards 1978; Loch Kinord, Vasari and Vasari 1968; (3) Lochnagar, Dalton *et al*. 2005; (4) Glen Clova, Roineach Mhor, Lowe and Walker 1977; (5) Eastern Glen Affric, Loch an Amair Froyd 2005 (6) Dubh Lochan (Loch Ness), Froyd and Bennett 2006; (7) Western Glen Affric, Torran Beithe, Carnach Moor and Camban Davies 2003a and b; (8) Loch Maree, Birks 1972; (9a) Loch Clare (9b) Loch Sionascaig) and (9c) Loch Craggie, Pennington *et al*. 1972; (10) Beinn Dearg, Binney 1997; (11a) Loch Strathy and (11b), Lochan by Rosail, Gear 1989; (12) Farlary, Tipping *et al*. 2008; Rannoch Moor (13a) Corrour Station and (13b) Kingshouse, Walker and Lowe 1981; (14) Rannoch Moor, Loch Tulla, Ward *et al*. 1981 and Bridge *et al*. 1990; (15a) Slamannan Plateau, (15b) Lochend Loch (Coatbridge) and (15c) Walls Hill Bog (Johnston), Ramsay and Dickson 1997; (16) Dumfries and Galloway, Birks 1974; (17) Isle of Lewis; (18) Isle of Skye; (19) Cape Wrath.

2.2 Preferred conditions for growth of *Pinus sylvestris*

Pinus occupies such a great variety of habitats that it is difficult to generalise briefly about the preferred conditions for its growth. *Pinus* is found from southern Spain to northern Russia, and from western Scotland to central Asia (Carlisle and Brown 1968). The geographical extent of *Pinus* is determined mainly by temperature as seeds require at least four months with temperatures in excess of 10.5^{o}C to ripen and 8.5^{o}C is required to produce vegetative growth (Mikola 1962).

Development of cones by *Pinus* individuals is determined principally by environment factors**.** Individuals of *Pinus* can produce cones as early as the second year of growth and typically *Pinus* will produce cones within ten years of germination (Lanner 1998). Latitude and altitude have a negative correlation with viable seed production in *Pinus***,** but it is unclear whether this is as a result of reduced pollen production in climatically stressed contexts (Crawford 2008). Seed production takes two years between initial development of strobili (cones) and the maturation of seeds within the cone (McVean 1963a).

Outcrossing is the dominant mode of fertilisation in most *Pinus* species and *P. sylvestris* is no exception. Ledig (1998) gives the percentage of successfully self-pollinated trees as between 9% (from Muona and Harju 1989) and 6.4% (from Yazdani *et al.* 1989). Of self-pollinated seeds, only 13.4% matured, as opposed to 71% in outcrossed seeds (Lanner 1998). Many individuals release pollen before peak female receptivity (Ledig 1998).

The potential for seeds to move far from a parent is dependent on the seed fall velocity, the wind speed and turbulence. These are likely to increase at the edges of woodland or in open areas between scattered trees. Bennett (1984) describes long distance dispersal as rare, occurring by chance, but affirms that long distance dispersal is important in the spread of *Pinus*. Birks (1989) describes an (un-testable) hypothesis, ‘jump dispersal’, *sensu* Pielou (1979), to explain the location of *Pinus* in Galloway 100km from seed sources in Ireland. Distal dispersal increases the chance of a single tree expanding the species range but lowers the chance of that tree reproducing successfully, making development of woodland, even if conditions were suitable, less likely. McVean (1963a) noted stunted individuals growing ‘more than 2km from the nearest living tree’. Similar stunted individuals, *krummholz* trees, are found on Fiacall a Coire Cas (Figure 2.2), above the Cairngorm ski pistes, up to 2km from other mature trees. This suggests that *Pinus* has the potential to spread by two quite different strategies, as a woodland species or as lone trees separated by distance from a source area.

Seed dispersal and regeneration may be made more successful by mast fruiting. Tree genera that mast are frequently wind pollinated, though this link is largely circumstantial (Crawford 2008). They are characterised by ectomycorhizal relationships (e.g. Pinaceae, Fagaceae, Betulaceae). There is some evidence of mast fruiting within *Pinus*. Masting may be related to mineral deficiencies (Crawford 2008) including phosphorus, which has Masting may result in more variable pollen production as well as variable seed production. It may be that been shown to be deficient in many environments occupied by *Pinus* **(**Landeweert *et al*. 2001). Decline of available phosphorus has been implicated in forest decline in all latitudes (Wardle *et al*. 2004). Mast fruiting is more common in climatically marginal locations, with longer return periods for more marginal locations. In Finnish Lapland and northern Norway masting can occur very infrequently, every 60 to 100 years. In other marginal environments such as Scandinavia, mast years occur on the order of every 10 years.

Figure 2.3 Fiacaill Coire Cas with the location of the highest *Pinus* individuals (arrowed) above the Cairngorm ski area. Several *krummholz* individuals were growing there in spring 2007, around 2km from other pine trees. According to the Cairngorm Ranger Service they were not planted, they occupy the side of the ridge exposed to the prevailing wind, making distant seed transfer possible

short-recurrence mast years could be identifiable in annually deposited sediments (e.g. varved lake sediments), but this has not been demonstrated. In mixed or bioturbated sequences mast years are unlikely to be apparent.

Almost no species of *Pinus* are capable of vegetative regeneration: exceptions are *P. mugo* and *pumila* (Lanner 1998); reproduction of *P. sylvestris* is therefore dependent on seed germination and subsequent seedling growth. The optimum temperature for seed germination is 21^{o}C. Temperatures of 50^{o}C or more will kill dormant seeds, but in Scotland are likely only during fire events. Waterlogged surfaces can prevent germination, especially if the seeds are buried, but even in aerated substrates burial to a depth of more than 1.5cm can prevent the cotyledon from reaching the surface (McVean 1963a). Germination and establishment of seedlings is most successful on bare, un-compacted surfaces.

Seedling establishment is rarely inhibited by nutrient deficiencies but nitrogen, phosphorus and other nutrients become important to subsequent growth (McVean 1963a, 1963b, Landeweert *et al.* 2001, Wardle *et al.* 2004). McVean (1963b) and Deluca *et al*. (2002) have related nitrogen availability to successful mycorrhizal inoculation: low nitrogen levels may check growth after the few first years.

Despite the fact that individuals of *Pinus* can clearly be adversely affected by fire (Bennett 1984), conditions for woodland are improved by fire (McVean 1963b, Berglund *et al*. 2004) as the input of charcoal helps to remove mycorrhizal inhibitors (Zackrisson *et al.* 1996). Fire also clears the ground of a variety of competitors that produce mycorrhizal inhibitors (Wardle *et al*. 2003). However, even in fire-generated clearings *Pinus* rarely adopts the role of pioneer if in competition with other trees, for example *Betula*, (McVean 1963a, Carlisle and Brown 1968, Crawford 1997).

Environments in which *Pinus* survive include a range of freely drained non-calcareous soils and heaths where thin peat overlies well-drained coarse sand (Carlisle and Brown 1968). A common habitat in Britain is along river valleys with free draining floodplains and terraces; in Scotland there is a tendency for *Pinus* to be on northward facing slopes (Carlisle and Brown 1968). It is able to survive in nutrient-poor conditions that exclude other species (Bennett 1984); thick peat is commonly colonised by *Pinus* but the more exposed and wetter the site, the less it is likely to be present. Both habitats show *Pinus'* need for light and its poor competitive ability in relation to other woodland species (Crawford 1997).

Pinus also has a range of adaptive strategies to cope with drought conditions. These include a decreased stomatal concentration in needles (Jessen *et al.* 2007) and decreased rates of photosynthesis (Crawford 2008). There is evidence to link drought conditions with greater needle longevity. *P. longueva* in the White Mountains of California retains needles for up to 45 years, considerably longer than the 3-7 years needle residence for *Pinus* in woodland (Richardson and Rundel 1998). However, the effects of waterlogging are less well defined.

Growth by *Pinus* on the atypical environmental niche (*sensu* Bridge *et al.* 1990) of the blanket mire reflects the ability of *Pinus* to survive in relatively nutrient-poor conditions, and for ability to cope with wet conditions. In such marginal settings, particularly on wet mires, the health of the trees is likely to be poor and individuals relatively short-lived. On the open mire, a high water table induces pale needle colour, a result of the gradual asphyxiation or sub-optimal performance of the root system. However, if a bog with a normally high catotelm experiences intermittent drying, a tree may be able to survive for an extended period (Crawford 2008). Crawford (2008) inclines to the view that trees die slowly even when sub-optimal conditions prevent establishment of seedlings, rather than catastrophically over a single very wet year as put forward by McVean (1963a) and Birks (1975).

Crawford (1997) summarises the effects of waterlogging on plant function and growth. Carbohydrate starvation has been identified in oceanic climates, where mid-winter thaws encouraging early growth are followed by a return to cold conditions that can damage the young shoots. Trees are particularly likely to suffer root dieback during prolonged flooding (Crawford 2008), as a result of post-anoxic injury and carbohydrate starvation, potentially resulting in increased wind-throw in commercial and natural forests. In addition dieback of roots leads to dieback of the tree above ground including lowered needle mass (Figures 2.4 and 2.5).

2.3 Native woodland, core areas and peripheries

The present pine woods of the Eastern Cairngorms, including Mar Lodge, have been described as a primary or native population by a number of workers (Watt and Jones 1948; McVean and Ratcliffe 1962, Pears 1968, Watson 1983, Willis *et al.* 1998, Gimingham 2002). The use of the term 'native area' is problematic because there are clear temporal disconnections between extant woodland and macro-remains (McVean and Ratcliffe 1962, Birks 1975). The term 'native' may have remained popular because forest restoration is typically concerned with 'native' species and woodlands.

In forest management, definition is sometimes ignored, as in the Complete Native Woodland Inventory for Scotland, report to Forestry Commission Scotland and Scottish Natural Heritage (SNH) (Clifford and MacKenzie 2004). Clifford and MacKenzie (2004) use SNH's own classification, comprising native, formerly native, locally non-native, long established, recently arrived and non-native, with no accompanying explanation or reference to an explanation of the meaning of ‘native’.

Native tends to be used implicitly to indicate the original species of a specific site or area (Sagoff 1999). This is a curiously British (or island) approach. It is of little relevance on the European Mainland where contiguous land allows species to migrate (Peterkin 2001). Steven and Carlisle (1959, page 4) describe native as ‘descended from one generation to another by continuous means’. This defines extant populations succinctly, but could exclude taxa occupying an area intermittently or expanding its range as a result of climate change. Furthermore, *Pinus* grows successfully as an isolated individual but produces mainly non-viable seeds when self-pollinated (Section 2.2). Such individuals may not provide continuous descendants and so could be argued as non-native. The question of viability is acknowledged by Steven and Carlisle (1959) and forms a key difficulty for those identifying past populations of *Pinus* by means of sub-fossils. Gear (1989) argued for viability in her analysis of past *Pinus* stumps in Loch Strathy; while the average age of *Pinus* stumps was low (54-65 years) the duration of occupation (241-275 years) suggested a viable, i.e. regenerating population. Distinguishing such a viable population from a non-viable population using palynological evidence is the problem at the heart of recent analyses utilising pollen and stomata (Froyd 2005).

Peterken (2001, page 271) suggests using ‘native’ in the ‘strict’ sense of the word: ‘native to the site, i.e. a species is native only if it is likely to be a past natural component of woodland on the….site’. This effectively replaces the word under discussion from ‘native’ to ‘natural’, which for most refers to processes without anthropogenic interference. Referring to ‘past natural’ dispenses with recently arrived

Figure 2.4 *Pinus* on mire, near Braemar. Few or no trees grow past the stage of the foreground individual.

Figure 2.5 The same mire as Figure 2.4, trees on the mire have thinner canopies than those in the background. Less obviously they also have lighter coloured needles.

species such as sycamore (*Acer pseudoplatanus*), which having been introduced now thrive without further help from people.

Defining 'native area' is recognised as difficult, leading to the use of various qualifying terms. The term 'potential area', first used by McVean and Ratcliffe (1962), is subsequently used by Birks (1975), Bennett (1984, 1988) and Richardson and Rundle (1998). It seeks to define 'native' in terms of edaphic and climatic tolerance. Slight changes in climate may change local conditions (Dubois and Ferguson 1985, Pears 1985, Tipping 2008) determining the suitability of an area to be colonised. Dispersal of *Pinus* seeds means that trees can migrate rapidly and colonise new areas, such as Caithness and Sutherland (Gear and Huntley 1991, Charman 1994), high slopes above Glean Einich (Binney 1997) and Sgor Mor (Pears 1968) in the Cairngorms, and even islands such as Rum and Skye (Birks 1975). *Pinus* seed dispersal (Section 2.2) means potential area is not necessarily tidily geographically constrained. The trees are 'native' wherever they are found, but the 'potential' area is variable (and can be surprising, see Figure 2.6) with changing conditions, including

Figure 2.6 *Pinus* seedling occupying potential habitat in Perthshire

changes in climate and human activity.

The differences between Figure 2.7 (from Bennett 1984) and Figure 2.8 (from Tipping 1994) reflect to some extent their respective ideas and ideas. The figures take similar baseline dates to map woodlands at their greatest extent. Bennett (1984) acknowledges that this date is before the spread of *Pinus* onto the blanket peat of Caithness at *c.* 4500 cal BP. The baseline also precedes the early Neolithic period, during which people may have caused major vegetation change (Edwards 1978, Bennett 1984 and 1989, Tipping 1994). There is palynological evidence linking vegetation change with Mesolithic activities (Simmons 1996, Hornberg *et al.* 2004) but these are localised in time and space.

The main areas shown as *Pinus* woodland by Bennett (1984, Figure 2.7) and Tipping (1994, Figure 2.8) are similar. In the west different extents of *Pinus* and *Betula* woodland are the result of slightly different criteria: Tipping uses pine or pine-birch woodland whilst Bennett prefers to map a single predominant taxon. As a consequence of this Bennett also shows *Pinus* woodland along the Aberdeenshire coast, the Black Isle and Easter Ross coast, which Tipping does not recognise.

Changes in the range of *Pinus* imply an area from which to expand, that is not adequately described by the term ‘native area’. During full glacial conditions, *Pinus*, like other arboreal taxa, survived in refugia (Bennett and Provan 2008). Unlike other taxa these refugia may have been located in or around the British Isles. Genetic evidence suggests *Pinus* in Scotland has two distinctive populations located in west and east Scotland (Kinloch *et al.* 1986; Sinclair *et al.* 1998). The Minch, between mainland Scotland and the Hebrides, and the North Sea, have been suggested as ice-free at the Last Glacial Maximum (Sissons 1979, Gaffney *et al.* 2007). Even if these areas served as seed source areas for Scotland, they are not areas of expansion during

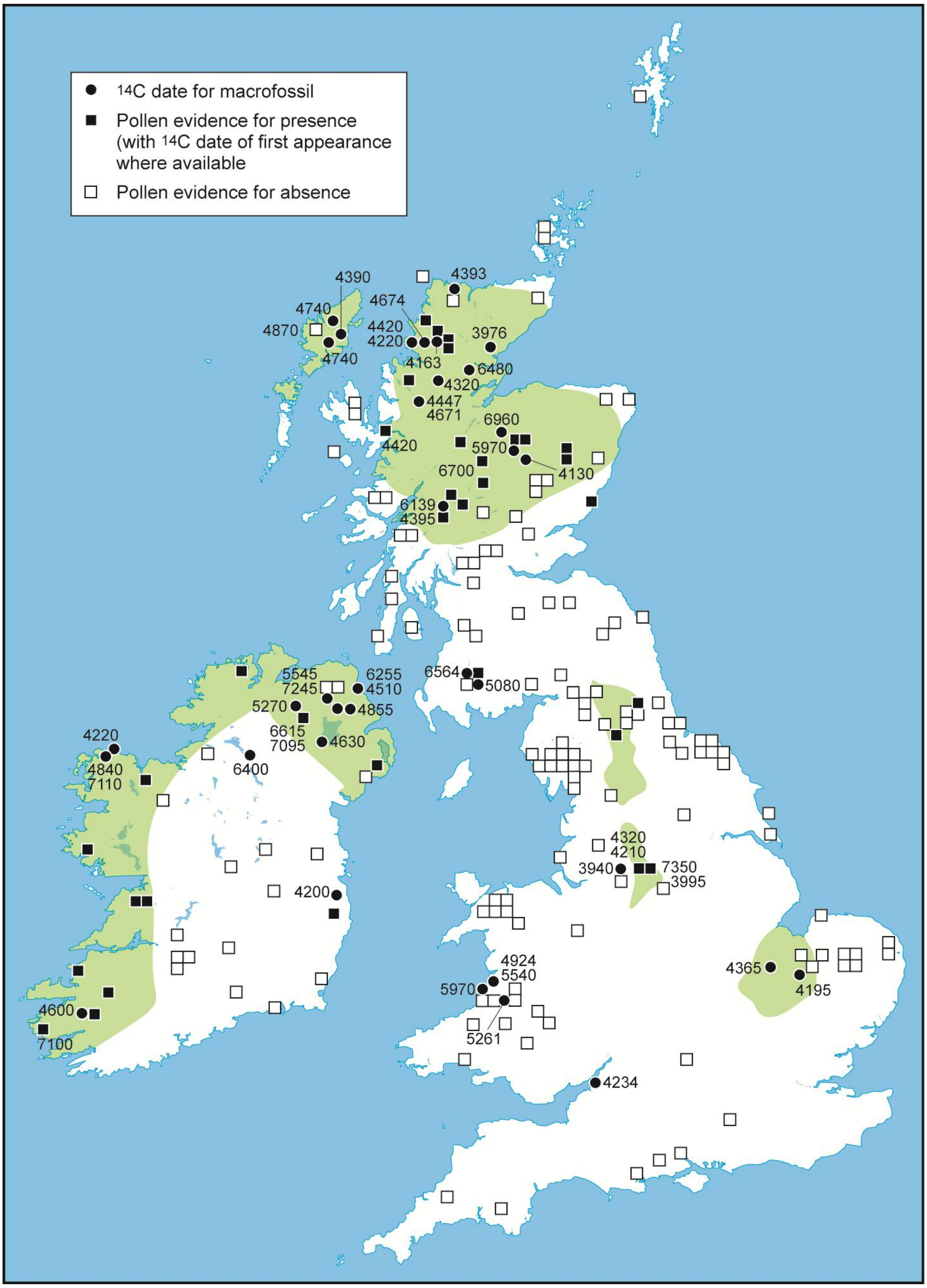


Figure 2.7 Distribution of *Pinus* c. 4500 cal BP (green shading), reproduced from Bennett (1984).

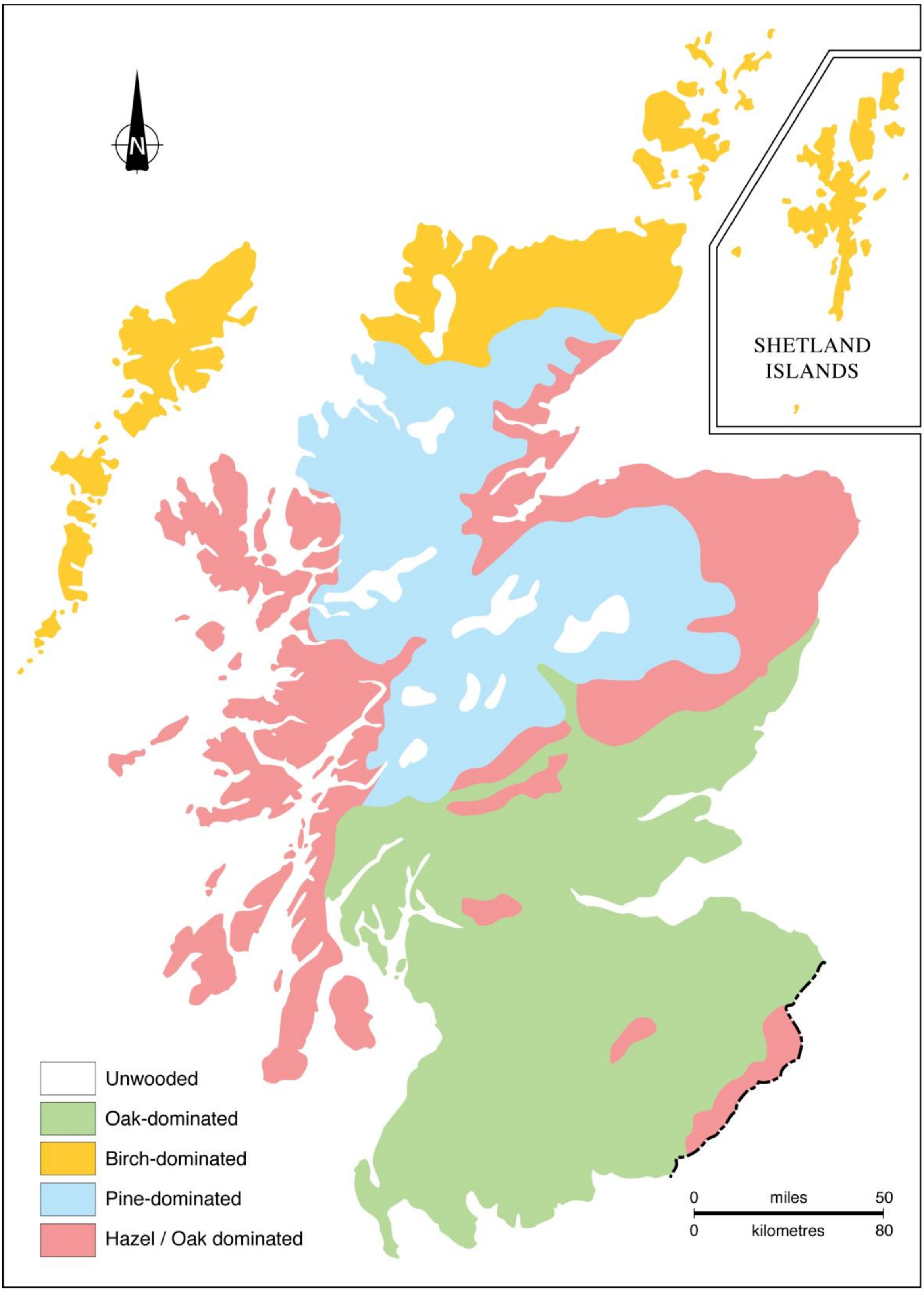


Figure 2.8 Major woodland types 3000BC, (*c*. 5000 cal BP) from Tipping (1994).

the Holocene. The term ‘core area’ has been used to denote areas of sustained occupation by *Pinus,* continuing to the present day (Tipping 1994), but not necessarily including either the oldest woodland areas or sites of first appearance of *Pinus*. It is largely consistent with the native areas of Steven and Carlisle (1959); areas that were probably colonised early in the Holocene and where *Pinus* remains. These are areas of maximum woodland stability which trees expanded from and withdrew to as conditions changed.

Core area need not imply native or potential area if early Holocene migration was initially to subsequently unfavourable localities. Bennett (1984) suggests that the only evidence for *Pinus* in Britain prior to *c.* 11600 cal BP is from Kent but Vasari and Vasari (1968) report two pine needles from Allerod age sediments (*c.* 12900-13800 cal BP) at Loch Kinord, Aberdeenshire. Both areas lie outside the area considered as ‘native’ or ‘core’ by most workers. The concept of core area implies the existence of a periphery. These are areas typically bordering the core areas that *Pinus* can colonise if suitable conditions arise, essentially potential areas. Peripheral areas include western Glen Affric, Loch Sionascaig in Inverpolly, Caithness, and montane slopes above the tree-line within core areas. Rannoch Moor is also typically regarded as a peripheral area, although areas of the moor feature longer colonisation by *Pinus*.

2.4. Reconstructing past presence, extent and behaviour of Scottish *Pinus* woodland

When using any part of a *Pinus* tree to create a narrative of its past there are a series of questions to be asked, some general and others specific to understanding the role played by *Pinus* in the Holocene. These might be framed thus:

1. How do sub-fossils relate to the local presence of a tree?

2. When was the local presence of *Pinus* first recorded?
3. What factors influenced local establishment?
4. Did expansion immediately follow establishment; what influenced this timing?
5. What plant communities were affected by expansion?
6. What else grew with *Pinus* and were these competitive relationships?
7. After expansion, does the evidence suggest dense or open woodland?
8. What affected the vigour, abundance and density of the population?
9. When and why did the population cease to be viable?
10. Which plants replaced *Pinus*?

There are two sub-fossil forms used to generate scientific data to reconstruct the former presence and abundance of *Pinus* woodlands: (1) macroscopic plant remains, especially stumps, and (2) microscopic remains, pollen and stomata. Coleopteran assemblages have begun to yield data regarding the past distribution of *Pinus*. Some historians have also used place-name evidence (McVean & Ratcliffe 1962; Smout 1997) and reference to the use of pine stumps as building material and firewood appear in old Highland estate records (Pears 1970a), but the interpretative difficulties of these sources render this information unreliable.

Studies of *Pinus* macroscopic plant remains often stand alone and independent of other data. In the past, pollen analysis has been carried out as a technique on its own but now routinely includes the recording of stomatal guard cells to overcome the interpretive difficulties. Pollen and stomata will be considered together in this Chapter.

2.5 Macroscopic plant remains

2.5.1 Research history and background

Initial observations by Lyell (1856), Lewis (1906, 1907, 1911) and Samuelsson (1910) catalogued stumps identified as *Pinus* in layers of peat in many areas of Scotland. Lewis and Samuelsson considered that these layers were broadly synchronous and could be correlated. This assumption has gradually been abandoned after a series of studies (e.g. Birks 1975, Dubois and Ferguson 1985 and 1988, Pears 1970b and 1988, Birks 1989) found a wide range of ages for stumps (See below, this Section).

The identification of macroscopic *Pinus* plant remains is generally straightforward (Bennett 1984), with all parts of the plant readily identifiable. *P. sylvestris* is the only *Pinus* species, and one of only three coniferous genera (together with *Taxus* and *Juniperus*), considered native to Britain in the Holocene (Section 2.3). The status of *Taxus* (yew) as a native is questioned (Dickson 1993) and it is rare in Scotland today (Stace 1991). *Pinus* needles are generally longer (20-80mm) than either *Taxus* (10-30mm) or *Juniperus* (4-20mm). Cones of *Pinus are* 25-75mm long, *Juniperus* 5-10mm, whilst *Taxus* bears a single 10mm ovule. They also differ in needle configuration; *Pinus* typically produces needles in pairs, *Taxus* in spirals and *Juniperus* often in whorls of three. There are morphological differences between needles other than length (Stace 1991), but these structures are rarely preserved in the fossil record. There are differences in the wood, (*Taxus* is non-resiniferous), as well as microscopic characteristics which require laboratory analysis.

2.5.2 Woodland and environmental reconstruction

There are difficulties in using data from macroscopic remains in mapping former presence of woodland. Clear differences in appearance between conifer genera do not preclude mis-identification of *Pinus.* According to Dickson (1988), sub-fossil

Alnus stumps are often mistaken for *Pinus* and as few localities have been re-examined with the diligence shown by Dickson, it is possible that numbers and locations of *Pinus* macrofossils are an over-estimate. In pre-20th century literature 'fir' is synonymous with *Pinus*, therefore taxonomic errors may be present in early work.

When correctly identified, macroscopic plant remains confirm the former presence of trees, but cannot demonstrate the existence of woodland. For example, Bridge *et al.* (1990) failed to show dendro-ecological correlations between individual trees in the same bog. Precise dating can be problematic; in the early literature (e.g. Lewis 1906, 1907 and 1911) correlations were made on stratigraphic grounds and subsequently often found wanting. More recent studies (e.g. Birks 1975, Gear 1989) are more chronologically reliable, but radiocarbon dated or dendro-ecologically correlated samples represent only a small part of the entire population of trees, even at one site.

The most common method for identifying the locations of macroscopic remains, particularly of stumps, is by walking along eroded or cut banks of peat (Wilkins 1984, Bridge *et al.* 1990). Many studies simply catalogue roadside stumps, for example, Wilkins' (1984) map of stump location can be mapped onto the roads of the Isle of Lewis (Figure 2.9). Other localities remained unvisited until recently: Birks (1975) shows a small area south and east of Cape Wrath as devoid of stump remains; a single example is marked on Gear and Huntley's (1991) map. Bennett's (2005a) diagram (Figure 2.10), showing the locations of all macroscopic *Pinus* remains in Scotland known to him, demonstrates that this gap in information is largely resolved. Practicalities are also important: to thoroughly investigate the short lived *Pinus* phase at Clashgour, (Rannoch Moor) a 2-3m depth of peat would have to be stripped from 'extensive areas' (Ward *et al*. 1987, page 222).

Sub-fossil stumps also present difficulties of interpretation. Bridge *et al.* (1990) note that ‘the impression imparted by the field evidence, of single layers of *Pinus* exposed near the surface of eroding blanket peat, appears to be highly misleading’. Bridge *et al.* (1990) suggest that during mire colonisation tree density was highly variable. The appearance of closely spaced, contemporaneously growing trees is an artefact caused by the interruption of peat growth by the solid barrier of the tree and subsequent stump. It is likely that apparent layers of stumps result from stratigraphic conflation whereby stumps of very different age ‘settle’ in one apparent layer. It is not possible to conclude from stumps alone the density of trees at any time or to conclude much about the nature of the vegetation accompanying the trees on the mire.

Sub-fossil macroscopic remains of *Pinus* are subject to the same vagaries of preservation affecting any fossil. Fossils are preserved only under certain conditions, including an accreting basin where conditions (e.g. anaerobic conditions) allow preservation of organic material. Bridge *et al.* (1990), for example, acknowledge that on Rannoch Moor they could not demonstrate that *Pinus* grew on mineral substrates because stumps would not have been preserved there. They suggest that those periods for which there are dated *Pinus* stumps represent incursions by *Pinus* onto the otherwise atypical edaphic setting of blanket peat. Dubois and Ferguson (1985) concluded that groups of apparently similarly aged *Pinus* stumps are likely to be due to optimum preservation conditions, not optimum conditions of growth. This demonstrates the impossibility of revealing all individuals trees in a woodland.

The oldest radiocarbon dated stump in an area does not necessarily indicate the first tree growing; nor does the youngest necessarily indicate the last tree to be growing there. The nature of the fossil assemblage, if completely independently dated,

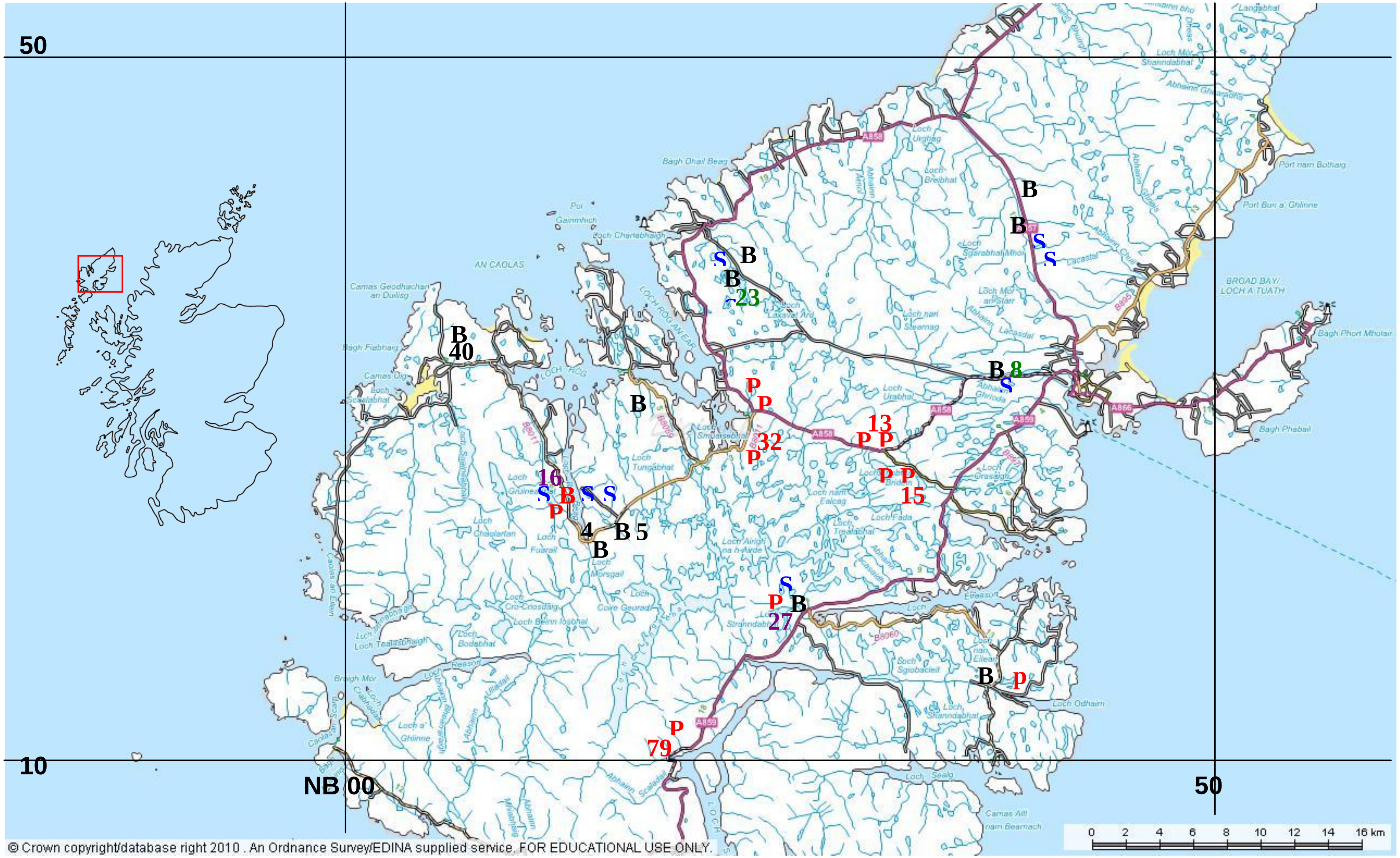


Figure 2.9 Macro-fossils of *Betula* (B), *Pinus* (P) and *Salix* (S) located on the Isle of Lewis, redrawn from Wilkins (1984). Numbers indicate radiocarbon dated macrofossils of *Betula* (black), *Pinus* (red), *Betula* and *Salix* (green) and all three (purple). Marginal numbers are part of 100km square NB of the national grid.

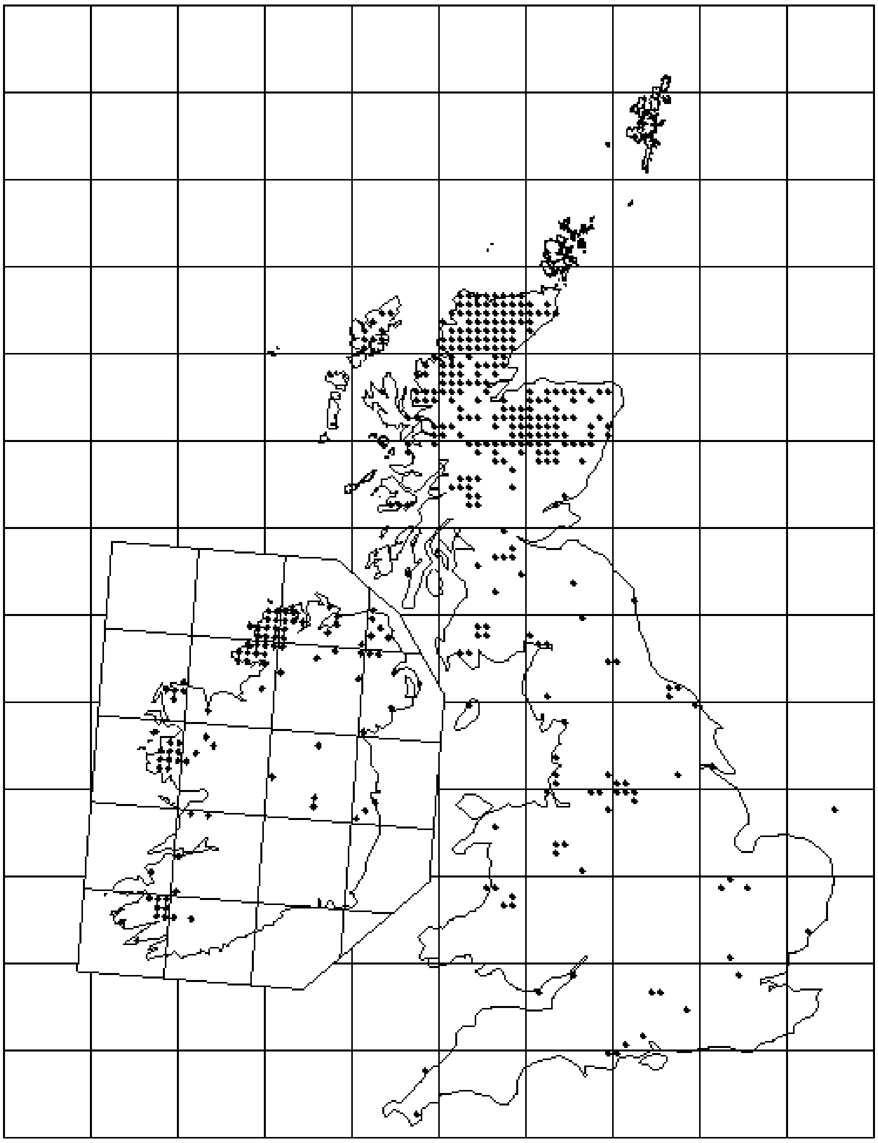


Figure 2.10 Location of Holocene macrofossil remains of *Pinus* from the British Isles (Bennett (2005a). The records are located by 10km squares of the British and Irish national grids, and indicate presence (solid dot) or no record only. The map is updated from versions published by Bennett (1984) and Bennett (1995).

can suggest gaps in growth, but not necessarily the complete record of such gaps. The tendency for stumps to appear in layers in peat probably has little to do with tree density during growth and more to do with preservation of the peat surface during and after tree growth. The main focus in this section is therefore on the location of trees, together, where possible, with evidence for temporal patterning.

Figure 2.10 (Bennett 2005a) shows *Pinus* stumps have been found in most regions, but are most common in the Highlands, north west of the Highland Boundary Fault. Caithness, shown by Gear (1989) to have significant numbers of stumps, is now without an extant population.

The Rannoch Moor area has been extensively studied (Ward *et al.*1987) with *Pinus* stumps dated to between *c.* 7400 cal BP and *c.* 3200 cal BP. Further south, Ramsay and Dickson (1997) reviewed discoveries of radiocarbon dated *Pinus* stumps in Central Scotland, from Slamannan (*c.* 3100 cal BP); Lochend Loch near Coatbridge (*c.* 6060 cal BP and 5760 cal BP) and Walls Hill Bog, near Johnstone (*c.* 4760 cal BP). Although detailing a wide spread of temporal and spatial patterning, Ramsay and Dickson (1997, page 144) ascribe these occurrences to rare events, a result of pine's ability "to colonise drier areas of peat bog, where there was limited competition from other tree species". Their conclusion, that *Pinus* occurred as isolated groups or individuals, without producing enough pollen to appear in pollen diagrams, accords with the idea of dual ecologies of *Pinus*, as a woodland species, and as an opportunist coloniser distant from 'core areas'.

According to Bridge *et al.* (1990), radiocarbon dated stumps from the Cairngorms comprise 60% of all radiocarbon dated *Pinus* stumps in Scotland, and show the Cairngorms to have been consistently occupied by *Pinus* throughout the Holocene. Interest has often been focused on the changing altitude of the tree-line, the assumption being that the *Pinus* population is a primary population, fluctuating throughout the Holocene. Pears (1968) identified two layers of stumps in many of his sites, including stumps preserved as high as 793 and 701m OD, significantly higher than the only tree-line considered natural today, 693m OD on Creag Fhiaclach (McConnell and Legg 1994). Pears refers to three pollen diagrams (Sgor Mor, Loch Eidart and Carn Mor) to relate stump layers to Boreal and Sub-Boreal times. The correlation with climatically defined periods of the two identified stump layers was felt by Pears (1968) to be tentative due to local factors linked to preferential preservation. Subsequent radiocarbon dates (Pears 1970b) showed the author's circumspection to be justified. He concludes that "topographical factors may be so important in mountain regions as to modify severely the influence of regional climate changes which are discernible elsewhere" (Pears 1970b, page 543), a view supported by Bridge *et al.* (1990).

Dubois and Ferguson (1985) also took the view that most stumps are present due to good preservation conditions rather than an increase of *Pinus* during good growth conditions. Their main contention, that changes to deuterium/hydrogen (D/H) ratios indicate changes to rainfall rather than changing temperatures, seems to be at odds with others investigating D/H ratios. The radiocarbon dates of Pears (1970) and Dubois and Ferguson (1985) show the presence of *Pinus* at altitudes above 480m OD between *c.* 8200 and 1050 cal BP. Huntley *et al.* (1997) report macrofossil data for a small lake, Lochan Oir (for location see Figure 3.1), about 15km north of Braemar in the Cairngorms. Bark and seeds from the Lochan extend local *Pinus* presence back to *c.* 8200 cal BP.

The nature and extent of macro sub-fossils mean that beyond giving a 'no later than' date, they provide little evidence regarding arrival time. Nor is there much to be said about the areas occupied by trees: if they happen to occupy a site not promoting fossilization they will leave no trace. Even a very large and detailed survey may not show the full extent of past *Pinus* locations, and cannot chronologically constrain the presence of trees or woodland.

Stumps can however potentially provide information directly concerning the appearance of the trees themselves if preserved, sampled and dated in large enough numbers. The dendro-ecological study by Bridge *et al.* (1990) on Rannoch Moor, approaches the numbers required to do this. *Pinus* on Rannoch Moor is characterised by low densities of trees, generally living to no more than 125 years on what Bridge *et al.* describe as the atypical ecological niche of the acidic mire. Gear (1989) analysed enough material in Caithness to show age of trees at death as at most equal to those on Rannoch Moor (Section 2.3). These datasets give direct and indirect evidence as to the appearance of trees on peat; individuals are small or stunted and have poorly developed canopies (Section 2.2, Figures 2.4 and 2.5). Tipping *et al.* (2008) report older trees (137-368 years old) growing on peat at Farlary, from a sample of 6 trees.

Evidence of demise from an absence of macro sub-fossils is always tentative. As *Pinus* individuals are very likely to have grown on substrates that did not preserve macroscopic remains it remains possible that a subsequent find could overturn the consensus view. Careful study of a large assemblage of sub-fossils might reveal detail about reasons for that assemblage's disappearance, but this appears to have been attempted only once, on Rannoch Moor. Bridge *et al*. (1990) did not establish whether trees grew after the death of sampled stumps, or what killed them. Tipping's (2008b) data on the same group of trees, suggested that they were blown over by very strong westerly but possibly atypical winds.

In summary, macroscopic remains in life position reflect where trees have grown and been preserved but are unable to resolve first or last appearance of all individuals, total cover or character of the assemblage. Viability of the trees can be inferred by dendro-ecological study, but this information is still subject to preservation biases. Dendro-ecological studies cannot determine when trees ceased growing in an area, though they can yield information about the cause of death.

Several areas with extant populations of *Pinus* are outside core areas, both Dumfries and Galloway and Caithness have several generations of independently dated stumps. Caithness stumps represent a major extension of the occupied area dated to *c.* 4500 cal BP. The core area of Rannoch Moor has been shown to have an extended occupation by analysis of stump sub-fossils found either buried or emerging from peat. The Cairngorms have the largest number of identified and dated stumps. Stumps found above the modern tree-line in the Cairngorms do not show chronological grouping. There are stumps in Glen Eidart as high as 750m above sea level (authors' own observations: September 2005 and July 2009), but Pears (1968) did not consider trees to have grown at his Eidart site, principally due to the lack of macro-remains.

2.6. Microscopic plant remains: history, interpretive problems and reconstructions

2.6.1 History of research

Pollen has been recognised as the male part of plants by western science since the late Seventeenth Century. Aboriginal populations, including Native Americans, may have recognised pollen for even longer (Traverse 1988), but improvements in optical microscopes helped develop pollen analysis only in the twentieth century.

Pollen analysis is held to be distinct from palaeo-palynology as it deals exclusively with extant species, with many analysts coming from a botanical rather than geological background. The earliest pollen analyst was probably a Swede, Lagerheim, who published simple pollen spectra from Swedish peat in 1900. Blytt and Sernander's (1905) climato-stratigraphic scheme influenced Lagerheim's microscopic studies just as it had formed the basis for studies of macroscopic remains.

In Britain, Harold Godwin was influential in developing Holocene pollen analysis; initially his zonation scheme was applied countrywide. This approach was gradually superseded as workers followed Cushing's (1967) suggestion to develop local pollen assemblage zones rather than to 'fit' pollen stratigraphies to a regional scheme. A series of pollen stratigraphies from northeast Scotland published by Durno (1956, 1957, 1958, 1958, 1959, 1960, 1961), provided real impetus to pollen analysis in Scotland. His work, and that of Nigel Pears, is now of lesser importance for several reasons. These include counts based on arboreal pollen, rather than Total Land Pollen (TLP) and low counts (e.g. Sgor Mor 150 pollen grains; Pears 1968).

Identification of *Pinus* pollen in the context of the British Holocene is straightforward, as there are no other bi-saccate pollen grains until the introduction of conifers such as *Abies* and *Picea* in the early modern period. The sacs aid dispersal of pollen, both in the wind and on water. Stomata are also very distinctive; the only taxonomic confusion in the British Holocene is with *Juniperus*. The recent keys by Hansen (1995) and Sweeney (2004) have resolved these difficulties. *Pinus* pollen and stomata are shown in Figure 2.11.

Palynology gained prominence partly because of the widespread occurrence of pollen in sediment. Pollen is highly mobile and found in abundance in a variety of sedimentary environments. Such environments are widespread, including soils, bogs, lakes, ponds and the sea (Moore *et al.* 1991). Not all environments give well preserved, easily identifiable pollen, or provide information within a stratigraphic context. Pollen in soil is particularly prone to aerobic breakdown (Traverse 1988) and the ready dispersal of pollen creates difficulties in using the pollen spectra to distinguish presence, abundance and location of plants in the landscape (Seppa and Bennett 2003). This is particularly true of *Pinus,* which produces large amounts of easily dispersed pollen. Inclusion of stomatal guard cells in routine pollen counts introduces a sub-fossil with the characteristics of a macrofossil into the analysis. This

Figure 2.11 Microfossils of *Pinus*, images under light microscope. Left, *Pinus* pollen; right, pine stomata, from Doire Bhraghad, 80cm.

helps resolve some of the interpretative difficulties of pollen analysis, particularly local presence of *Pinus* when pollen percentages are low (Froyd 2005).

2.6.2 Defining source areas of pollen

In pre-Quaternary studies, higher concentrations of palynomorphs (spores, pollen and dinoflagellate cysts) are regarded as indicative of a more proximal source, and the same is true of Quaternary assemblages (Traverse 1988). The delivery mechanisms of pollen to a deposit have been described in detail by, for example Tauber (1965) and Jacobson and Bradshaw (1981). Jacobson and Bradshaw's (1981) diagram (Figure 2.12) shows that the pollen source area for a lake deposit increases with lake surface area. Vegetation form also affects the form of pollen delivery

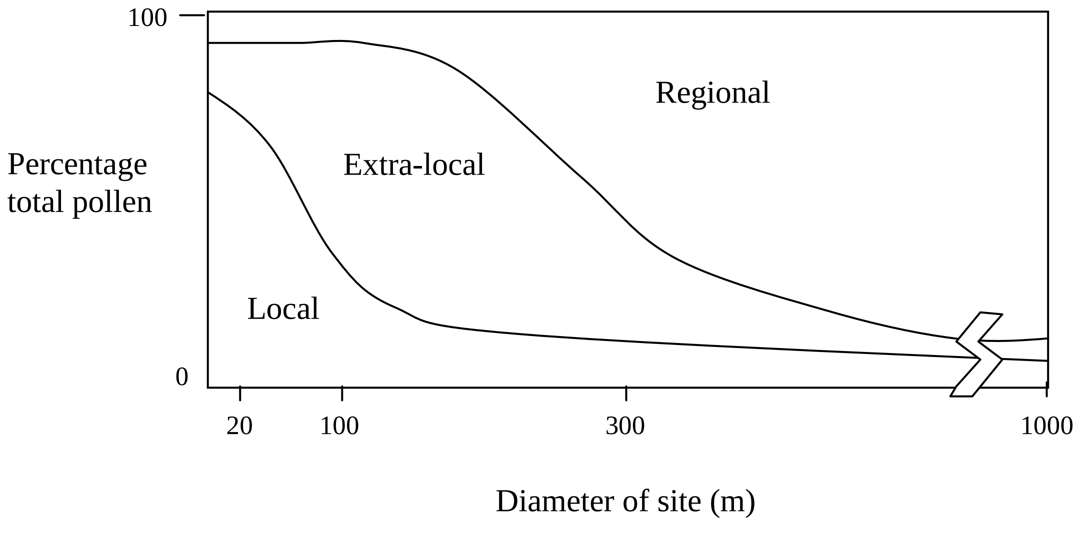


Figure 2.12 The relationship between site diameter and pollen source, reproduced from Jacobson and Bradshaw (1981).

(Prentice 1988), for example, a closed canopy reduces wind speed, promoting the through trunk space and gravity components of pollen deposition (Calcote 1998).

The tendency for lakes with larger surface areas to reflect increasingly distal pollen sources is due to the decrease in importance of local and extra local pollen sources *sensu* Jacobson and Bradshaw (1981) and increasing fluvial input from the wider catchment. Sugita's (1993, 1994) models define average pollen loading (input) of a given species at a given site, and his simulations define a relevant source area for pollen (RSAP), defined as the distance from a basin after which there is no further improvement in the correlation between pollen and vegetation. The approach works best for pollen assemblages in forested environments. Sugita defined the RSAP for small hollows (2m diameter) as 50-100m radius, for small lakes (50m diameter) as 300-400m radius and for medium sized lakes (250m diameter) as 600-800m radius. Calcote (1995) found that in forest situations there was little increase in correlation between pollen and vegetation between 50 and 100m.

Working in northwest Scotland, Bunting (2002) suggests that the RSAP for arboreal taxa is *c.* 300m for peat samples, but more than 400m for small lakes. This is in agreement with the view that pollen from moss polsters closely reflect local vegetation (Jackson and Kearsley, 1998). Bunting (2003) found that non-arboreal pollen such as *Calluna vulgaris*, *Vaccinium* type, *Myrica gale*, Cyperaceae and Poaceae, RSAP was considerably smaller, on the order of 2m or less. Moss polsters in Scotland are typically surrounded by these non-arboreal taxa, which may be high pollen producers (Fossit 1994a, Brostrom *et al.* 2004) suggesting that separating canopy and understory dynamics may be made more difficult by the improvements in quantitative analysis.

2.6.3 *Pinus* pollen and pollen diagrams

Bennett (1984, page 138) argued that ”radiocarbon dates from individual macrofossils (or their surrounding sediment matrix) establish the presence of an individual of *P. sylvestris* at one locality at one point in time”. Unfortunately it is not possible to make such a statement with regard to even a well-dated pollen stratigraphy (Section 2.6.2). Lowe and Walker (1977) considered that a *Pinus* component of 45% TLP at Roineach Mhor, Glen Clova, represented an extra local or regional population overwhelming very low local pollen productivity and Bennett (1984) in agreement with Lowe and Walker (1977) considered *Pinus* to be generally over-represented within pollen diagrams. Sugita *et al.* (1999) showed that pollen productivity for *Pinus* was greater than *Alnus* but less than *Betula* and *Quercus*; in their study Poaceae was used as the unitary value, with *Pinus* seven times, *Alnus* five times, *Quercus* eight-nine times and *Betula* almost ten times that of Poaceae.

Studies by Birks (1970) and O’Sullivan (1974a, 1976) in Speyside and Birks (1972) and Pennington *et al.* (1972) in northwest Scotland interpreted pollen assemblages without consideration of what might represent local presence of trees. The relatively large surface area of the lakes sampled, means pollen is derived from mainly regional sources (*sensu* Jacobson and Bradshaw 1981) and interpretations are of vegetation on a regional rather than a local scale.

The idea of a pollen threshold for local presence of *Pinus* emerged soon after O’Sullivan’s studies. Lowe and Walker (1977) suggested that 40% TLP was the minimum required. Huntley and Birks (1983, page 306) suggested that 25% TLP was the minimum percentage to ‘confirm’ local presence. They also gave a value of 50% TLP as indicating local dominance. However neither Lowe and Walker nor Huntley and Birks explain how these numbers are derived. Favre *et al.* (2008) concluded that *Pinus* values of 19.8% could represent local trees, seemingly in agreement with the idea of a threshold, but neither Favre *et al.* (2008) nor Huntley and Birks (1983) suggest that less than 19.8 or 25% respectively must indicate an extra-local source of *Pinus*.

Bennett (1984) considered pollen spectra with *Pinus* exceeding 20% TLP (or 20% of tree and shrub pollen in diagrams excluding herbs) to be indicative of the local presence of *Pinus* but does not specify how he arrives at this conclusion. According to Bennett (1984, page 137), emphasis on the 20% threshold "highlight[s] pollen diagrams from areas where *Pinus* was a significant element in the surrounding vegetation". This might indicate, then, that *c.* 20% TLP indicates a *Pinus* woodland in some form, but perhaps not widely dispersed individuals in a heath; Bennett's purpose was to differentiate between common and scarce or absent. Bennett explains that it is not possible to distinguish a small amount of pollen produced by a local population from the long distance component of pollen rain.

Ward *et al.* (1987) followed Bennett (1984), concluding that it was 'reasonable to assume' that 20% TLP derived from peat samples was indicative of local presence. Bennett and Birks (1990) used 20% to indicate local *Pinus*, now based on moss polster samples from near and within *Pinus* woodland. Bennett (1984) stays implicitly close to Godwin's (1975) model of the appearance, local expansion and dominance. His main contention, that it is not possible to distinguish between a local and long-distance source from a low percentage of *Pinus* pollen, is in agreement with the more recent work describing RSAP (Sugita 1993, Bunting *et al.* 2004).

Bennett (1984) may have been slightly hasty in asserting that pollen data can provide evidence for absence in a particular area at a particular time, rather than suggesting likelihood of absence. Froyd (2005) considered that many pollen analysts misapplied Godwin's (1975) model of a taxon front migrating across a landscape, suggesting that many had correlated the rise to sustained percentages (local expansion) as an indication of local appearance. This is similar to the suggestion by Lowe and Walker (1982a) that *Alnus*' was present in very low numbers on suitable sites prior to environmental change that encouraged expansion. Froyd's evidence comes from stomatal and pollen analyses in lake sediment in Glen Affric, where stomata indicating very local trees were recorded in pollen spectra with *Pinus* pollen recorded at only 1% TLP.

The concept of an easily defined threshold for local presence of pine trees became more problematic as studies using surface samples showed that *Pinus* can be locally growing but still be a minor component of a pollen diagram in the pollen assemblage (e.g. less than 5% TLP, Fossit 1994b). Smith and Pilcher (1973) coined the terms rational and empirical limits for pollen spectra to indicate the first appearance and the consistent presence of pollen of a taxon in a diagram. Following Fossit (1994b), Froyd (2005) and Tipping *et al.* (2008) it has become clear that these terms, for *Pinus* at least, have little real meaning for interpreting vegetation. Even for taxa such as *Pinus*, which produces large quantities of pollen, defining local presence only by a high percentage TLP confuses local presence with much higher abundance of *Pinus*, as a woodland species. Under-representation may be particularly true of sparse populations of *Pinus*, such as on tree-lines or open moors where tree canopy is open and ground flora consists of heaths (Figure 2.13). Increased space between trunks results in increased wind speeds and more rapidly dispersed pollen (Bunting *et al.* 2004), residual, more lightly concentrated pollen can suffer aerobic breakdown prior to sedimentary incorporation. Ward *et al.* (1987) report highly variable percentages of *Pinus* from modern moss polsters in *Pinus-Betula* woodland, through open *Betula* woodland to open moorland. Within *Pinus-Betula* woodland percentages

Figure 2.13 The typically flat and windswept moorland of Lewis (above), is occasionally interrupted by more sheltered areas supporting small groups of small (planted) *Pinus* (below). This may be the kind of landscape in which viable communities of *Pinus* are almost palynologically invisible.

were high, 76- 91% TLP. In open *Betula* woodland with ground flora dominated by *Molinia* (purple moor grass), *Nardus* (mat-grass) and sedges, *Pinus* pollen averaged 43% TLP but with a range from 7-70% TLP. On a separate transect through woodland onto *Calluna* and *Erica* moorland, *Pinus* frequencies were as low as 1% 100m from the woodland edge (Ward *et al.* 1987).

Ground flora therefore seems to be important for the representation of *Pinus* pollen within pollen spectra, it is possible that as simple a mechanism as bushy dwarf shrubs preventing *Pinus* pollen reaching the ground is sufficient to distort representation. This is in agreement with Huntley *et al.*'s (1997) statement, that "the past position of a *Pinus sylvestris* tree-line cannot be traced effectively using palynological evidence alone, as tree-lines typically consist of a transition from woodland to heathland vegetation. Binney's (1997) study from the Loch Einich and Beinn Dearg areas used a 2% TLP threshold of *Empetrum* to indicate openness, regardless of high percentages of *Pinus*. This approach is based on the preference of *Empetrum* for very open conditions and potentially allows interpretation of openness independent of relative *Pinus* pollen abundance.

Measures of pollen influx are independent of relative pollen abundances, but suffered from methodological difficulties until the 1980's (Seppa and Hicks 2006). The densest network of methodologically sound pollen traps used to develop associations between certain forest and woodland types are across arctic and alpine tree lines in Fenno-Scandia (see below, Section 2.6.8). As such they must be used with caution in the Scottish context. The short time intervals over which useful data is available also makes caution sensible. The accuracy of pollen accumulation rates in palaeoecological studies is dependent on sound chronology, which for many early studies is not available. Reference to similarities between influxes should give useful corroborative information regarding canopy density, but it is probably unwise to base inferences on influx alone.

2.6.4 First appearance of *Pinus* in Scotland from microscopic remains

There is no strong evidence of *Pinus* presence in the Devensian Lateglacial of Scotland based on pollen evidence, though this may be due to the assumption of *Pinus* over-representation compared to other taxa in pollen diagrams. Lowe and Walker (1977) report high percentages, from Roineach Mhor, Glen Clova, but conclude this to show a distal population overwhelming low local pollen production (Section 2.6.3). This may represent a small number of trees growing locally but if present in the Scottish Lateglacial, *Pinus* was not abundant.

Birks (1989) reviewed available radiocarbon dated pollen stratigraphies and used them to construct isochrone maps showing Holocene migration across Britain for a range of tree taxa. Estimates of first appearance are shown for *Pinus* including in areas with a modern population, some dates have been superseded as new techniques evolved.

Some of the most northerly sites provide the oldest radiocarbon dates for first appearance but the data are difficult to interpret through the large surface areas of these lakes. Birks (1972) found the first appearance of *Pinus* in the Loch Maree area at *c.* 9250 cal BP; at nearby Loch Clair, Pennington *et al.* (1972) suggested that *Pinus* expanded into the area ‘somewhat later’ than *c.* 8600 cal BP. The more northerly populations of *Pinus* were established around Lochs Sionascaig and Craggie by *c.* 9000 cal BP (Pennington *et al.* 1972). Around Glen Affric, Birks (1989) follows Bennett (1984) in suggesting regional expansion by *c.* 8460 cal BP. In the same area, though, Froyd (2005) found pine stomata from samples dated to *c.* 9600 cal BP. At the western end of Glen Affric, at Torran Beithe, Davies (2003a) dates first appearance of stomata to *c.* 7950 cal BP, coincident with the rise in *Pinus* percentage to 20%; the beginning of this rise is at *c.* 8500 cal BP. It must be remembered that the two sub-fossils, stomata and pollen are proxies for different aspects of *Pinus* ecology. If increases in *Pinus* pollen are considered for Loch an Amair, dates are more similar: the rise in pollen percentages begins from *c.* 8400 cal BP.

The identification of *Pinus'* first appearance from Loch Pityoulish (*c.* 8900-7650 cal BP) is followed by a gradual rise (O'Sullivan 1976). O'Sullivan (1976, page 299) describes this as 'presumably' meaning that *Pinus* invaded, colonised and came to dominate the area, but because *Pinus* pollen can become concentrated in deep water means, "it may not be possible to state precisely when *Pinus* arrived in the locality". O'Sullivan also reports but does not detail, identification of stomata in the Loch Garten sequence, with increases in stomata numbers "about half way through the period of *Pinus* [pollen] expansion" (O'Sullivan 1976, page 299). This puts his tentative conclusion of 'probable presence' at odds with present knowledge, which would suggest that at Loch Garten *Pinus* would have been growing locally before *c.* 8400 cal BP. O'Sullivan's apparent uncertainty regarding stomata is reinforced by suggestions that stomata are absent from the sequence at Loch Pityoulish because they "do not appear to be so readily sedimented".

Birks (1970) and Birks and Mathewes (1978) combined macrofossil and pollen to confirm the arrival of *Pinus* woodland around Abernethy, in the western Cairngorm. The rise of the pollen curve occurs at *c.* 8350 cal BP. This probably indicates *Pinus* woodland rather than *Pinus* trees; the large source area for the loch diminishing the percentage of rare taxa. Deposition of *Pinus* needles begins at *c.* 7650 cal BP. Binney's (1997) site selection in the Cairngorms investigates movement of *Pinus* woodland altitudinally and examines the changing density of *Pinus* trees.

The lowest site, Allt-a-Phris Ghiubhais, 500m above sea level, is at a similar altitude to Birks' (1975) site at Loch Einich. *Pinus* was present locally here from *c.* 8200 cal BP. Binney's other study area, Beinn Dearg (near Inverness), has a low altitude site, Dime Mor (270m above sea level) at which *Pinus* may have arrived as early as *c.* 8400 cal BP, but was definitely present by *c.* 7700 cal BP.

In the north east of Scotland, Tipping *et al.* (2008) used pollen and stomatal evidence to show rapid *Pinus* colonisation between *c.* 7900 and 7500 cal BP. They note that local expansion was later than regional expansion (Birks 1989, Bennett 1995) at *c.* 9500-8500 cal BP but suggest no specific environmental factors for this difference.

Edwards (1978) suggests the possibility of *Pinus* presence in mid-Deeside prior to *c.* 8000 cal BP; intermittent peaks as high as 10% TLP at the base of the Loch Davan sequence make sparse local presence possible. Huntley (1994) carried out a study in the east Cairngorms, but his analyses do not satisfactorily cover the arrival in the area of *Pinus* as a result of an unconformity between *c.* 9500 and 6500 cal BP (117-100 cm) and a chronological reversal above 100cm. Pears' (1968) study lacks an independent chronology and Pears' (1970b) interpretation concentrates on higher altitude *Pinus* stumps without reference to pollen data. Binney's (1997) investigation of Moine Mhor (930m OD) suggests local scattered *Pinus* at *c.* 3800 cal BP.

Dalton *et al.* (2005) carried out a multi-disciplinary study from Lochnagar, the only one of its kind in the Cairngorms, but there is only brief discussion of vegetation history. *Pinus* and *Alnus* are suggested to have arrived in the area just 500 cal years apart, with *Pinus* arriving first at *c.* 8400 cal BP. There are no confirmatory macroscopic remains at Lochnagar but Dalton *et al.* (2005), note that Rapson (1985) published a radiocarbon date of 6805-7000 cal BP for a *Pinus* stump in Lochnagar Burn, at 600m OD.

Lowe and Walker's (1977) southern Cairngorm sites show only that *Pinus* colonises after *c.* 11500 cal BP, when *Betula* colonised the area. On Rannoch Moor increases in *Pinus* pollen dating from *c.* 7480 to 7650 cal BP (Bridge *et al.* 1990), indicate 'rapid colonisation'. The nature of the peat sample's limited source area means this is probably particularly true of the local area rather than the entire moor.

2.6.5 Factors influencing first appearance of *Pinus* and woodland expansion

The timing and location of the first appearance of *Pinus* in the early Holocene is dependent on the source locations (Section 2.2 and 2.3) and the speed with which plants are able to migrate from them. Movement from refugia is dependent on availability of habitat, which could simply be ice-free substrate. Abandonment of refugia may result from development of conditions not conducive to growth of *Pinus*. Refugia need not be synonymous with core areas (Section 2.3), but postulated refugia close to core areas would help explain early appearance of *Pinus*.

In continental Europe, climate amelioration at the start of the Holocene led to spread of *Pinus* onto suitable sites, reaching the Kola Peninsula by *c.* 9500 cal BP and becoming common there by *c.* 8900 cal BP (Kremenetski *et al.* 2004). *Pinus* reached maximum elevation in the Swedish Scandes Mountains by *c.* 10700 cal BP (Kullman and Kjallgren 2000). These observations reflect the importance of mean July temperature to *Pinus* viability, (Kultti *et al.* 2006), optimal from *c.* 10000 cal BP (Seppa *et al.* 2008).

The Scottish mainland was probably ice-free from *c.* 16000 cal BP, (Golledge 2010) following the glacial maximum around *c.* 21-21500 cal BP (Jones and Kean 1993). The Holocene thermal maximum, from *c.* 6700-8200 cal BP is closely identified with establishment of *Pinus* woodland. High seasonality (warmer summers, cooler winters) extended until *c.* 3900 cal BP, enabling *Pinus* to remain growing in areas north of its present location (Allen *et al.* 2007). However, although *Pinus* is mainly limited by temperature there are also locally important checks to colonisation. Tipping *et al.* (2008) found no reason for the late appearance of *Pinus* at Farlary, other than proximity to seed sources; and the first appearance in western Glen Affric was probably delayed by the length of time that *Pinus* took to migrate up the valley. Colonisation of the blanket mires in Caithness from *c.* 4500 cal BP was possible because of drying of the bog surface (Gear and Huntley 1991).

Pinus seeds can be blown long distances from the parent tree (Section 2.2), colonise areas distant from other *Pinus* individuals, and die leaving no successors; such lone pines are likely to be overlooked by palaeoecologists, influencing the record of first appearance. Nonetheless evidence for the first appearance of *Pinus* in Scotland, with the possible exception of Farlary and mid-Deeside, is in agreement with spread from the northwest. Movement of *Pinus* from the south is likely to have been quicker along the coast than along the Highland valleys, allowing *Pinus* to arrive in the northwest of Scotland early in the Holocene.

2.6.6 Separating local establishment and expansion

The extent to which it is possible to identify time lags between first appearance and local expansion of *Pinus* depends on the methods used and on data quality. The majority of studies pre-date the routine inclusion of stomata within analyses. Glen Affric is the only core area of woodland where stomata and pollen analyses show both the arrival and expansion of *Pinus*. Froyd (2005) found that at Dubh Lochan, (east Glen Affric) and Loch an Amair (mid-Glen Affric), first appearance of stomata pre-dates the increase of pollen by 600 cal years and 1600 cal years respectively. In west Glen Affric Davies (2003a) records an initial rise in pollen to *c.* 20% TLP and a first single appearance of stomata, at *c.* 7950 cal BP. A second increase to *c.* 40% TLP combined with consistently recorded stomata is dated to *c.* 7540 cal BP. Davies recognises adjustments in the initial woodland assemblage (see below, Section 2.6.7) as relating to the expansion of *Pinus*. At Farlary in the north east, Tipping *et al.*'s (2008) first appearance of stomata is coincident with a second rise in *Pinus* pollen frequency, an initial rise from *c.* 10% to 20% TLP at *c.* 8250 cal BP possibly representing sparse local presence.

In Gleann Einich Binney's (1997) use of *Empetrum* percentage to indicate the degree of openness suggests that *Pinus* at Alt A'Phris-Ghiubhais (500m) has *c.* 2000 cal years between first appearance and local expansion. In contrast assemblages at Lochan Odhar (700m) and Carn a'Phris Ghiubhais (630m) suggest simultaneous first appearance and expansion, emphasising the importance of local conditions.

On Rannoch Moor Bridge ***et al.***'s (1990) study shows a pollen rise in combination with stumps but whether this is expansion or appearance is unclear, possibly due to insufficient temporal acuity. Gear (1989) and Charman (1994), using very close sampling techniques on samples outside core woodland areas, show rapid vegetation changes. At Gear's site at Lochan by Rosail for example, the assemblage changes from *Betula* to *Betula-Pinus* to *Betula* woodland within *c.* 700 cal years (*c.* 5500- 4800 cal BP). The transition from *Betula-Pinus* to *Betula* woodland occurs within an assemblage indicative of disturbance.

2.6.7 Associated taxa

Even when *Pinus* is dominant, other taxa continue to grow with it, forming the local assemblage. Though the difference between the 2990 species of British vascular plants (Stace 1991) and the 390 types of pollen and spores following the same taxonomy and nomenclature (Bennett 1996, vad Odgaard 1999) is still apparent, developments in pollen taxonomy have helped improve definition of plant assemblages. The series 'The North West European Pollen Flora' includes Betulaceae and Corylaceae (Blackmore *et al.* 2003) and Myricaceae (Punt *et al.* 2002) while Foss and Doyle (1988) represents an earlier improvement within the Ericaceae. Better definition of the source of identified taxa has also improved definition of assemblages (Section 2.6.2).

Birks' (1972) Loch Maree study is taxonomically 'cautious', using combinations of *Betula*, *Betula*/*Corylus*/*Myrica* and *Corylus*/*Myrica*, to show birch-hazel woodland prior to the appearance of *Pinus*. At Loch Sionascaig and Loch Craggie, pine or pine–birch woodland also replaced birch–hazel woodland (Pennington *et al.* 1972). *Pinus* at nearby Loch Clair expanded into a "herb and fern rich birchwood, with much willow, and low percentages of hazel" (Pennington *et al.*, 1972, page 280). Oak and especially alder became important in the Loch Maree assemblage during the mid Holocene, but neither formed a sizable component in other areas. When *Pinus* woodland began to decline *Betula* remained important, with *Calluna vulgaris* forming heathland between fragmenting patches of woodland.

At Binney's (1997) Beinn Dearg site, *Betula* remained present after *Pinus* replaced it as the dominant taxon. Binney (1997) suggests that *Pinus* was able to establish in canopy gaps as *Betula* density decreased during a period of drying conditions. During the mid-Holocene, change between *Betula* woodland, *Pinus* woodland and heath took place in response to regional environmental change.

East Glen Affric is shown by Froyd (2005) and Shaw (2006) to have had a continual presence of *Pinus* from *c.* 9600 cal BP to the present. Shaw's sites were chosen to emphasize local vegetation and stratigraphies are dissimilar, with mixed woodland and cycling between woodland and heath more common than stable *Pinus*-dominated woodland (Shaw 2006). *Pinus* is more consistently present at the east end of the glen. At the furthest west of her sites, Torran Beithe, Davies (2003a) found that initially *Pinus* co-existed with *Betula-Sorbus-Populus* communities. *Pinus* became the dominant taxon by ousting both *Populus* and *Sorbus,* but *Betula* remained. Later rapid replacement of *Pinus* (see below, Section 2.6.9) by *Quercus*, *Alnus* and *Corylus* suggests they were already present at low densities in the area. Herbaceous and heath taxa became more important after *c.* 3890 cal BP.

The oldest of Shaw's (2006) sequences, PB, is in mid Glen Affric (Shaw 2006). At the base (*c.* 5260 cal BP) the pollen assemblage consists of 50% *Pinus* (with stomata) confirming woodland with *Betula*, *Ulmus* and other trees. During declines in *Pinus* (from *c.* 4500 cal BP) woodland remained diverse with *Betula* and possibly *Alnus* and *Quercus*. Remnants remained until *c.* 2500 cal BP. Two sequences further east (ANI and ARC) are no older than *c.* 3770 cal BP, but show almost continual local *Pinus* presence, in agreement with Froyd's (2005) sequence at Loch an Amair. The arboreal associations for these cores are less varied than further west. *Betula* is the main secondary taxon, but *Quercus* is also evident. There is good evidence of woodland / heath cycling. Furthest east three cores indicate more stable woodland over the last *c.* 4000 years. *Pinus* dominates with *Betula*, *Calluna* and latterly Poaceae.

On the west side of the Cairngorms, Birks (1970), O'Sullivan (1974a, 1976), and Birks and Mathewes (1978) agree that *Pinus* woodland invaded a landscape dominated by *Betula-Corylus* woodland (O'Sullivan 1974a, Birks and Mathewes 1978). At Abernethy Forest Birks and Mathewes (1978) use a combination of macrofossil and pollen evidence to show that increasing *Pinus* percentage probably indicates *Pinus* woodland replacing *Betula* and *Corylus*. The assemblage zones are in agreement with Birks (1970) undated sequence also from Abernethy Forest. Neither sequence is younger than mid-Holocene.

At Loch Pityoulish, O'Sullivan (1976) agrees that *Betula* continued to be important after *Pinus* became dominant. When *Pinus* declines after *c.* 5700 cal BP, the main replacements are *Betula* and *Quercus* rather than *Juniperus* and *Calluna*. In the mid to late Holocene as *Pinus* continues to decline, substitution of *Pinus* by *Betula* continues, with *Alnus* and NAP becoming important only after *c.* 900 cal BP.

Pinus pollen in the Loch Garten sequence increases to more than 60% TLP (O'Sullivan 1974a) at the expense of *Betula* and *Corylus*, though they remain important in the pollen assemblage until the mid-Holocene. After *c.* 3600 cal BP *Calluna* becomes more important but for the most part the understory around Loch Garten is composed of *Juniperus* and Gramineae (Poaceae). O'Sullivan's (1976) analysis from Loch a'Chnuic extends back to the Late-Devensian and is similar to others from the area; the main assemblages are of *Pinus-Betula* and *Pinus-Betula* with *Alnus*. Both O'Sullivan (1974a, 1976) and Birks (1970) regard *Betula* and *Alnus* as occupying areas that are spatially distinct from *Pinus,* rather than gaps within the *Pinus* canopy, therefore competition between the three taxa is limited.

Birks (1975) reports *Pinus* expansion around Loch Einich at the expense of *Betula* with *Corylus*. Once *Pinus* was established, *Betula* persisted as part of a mainly

Pinus-heath assemblage. Binney's (1997) sites above Gleann Einich found no evidence of tree cover before the arrival of *Pinus*. The movement of Binney's pine front into a *Calluna*, *Empetrum* and *Vaccinium* heath reflects the altitude of at least 500m OD. After *Pinus* establishment, Binney (1997) showed that *Calluna* and *Empetrum* continued to be important. In the same area Pears' (1968) study is too taxonomically limited to show anything with certainty. *Betula* forms a large component of the assemblage but the basis of the count (taxa expressed as a percentage of Arboreal Pollen) shows that Ericales are always the main component.

In the eastern Cairngorms near Braemar, *Pinus* woodland replaced scrub and woodland vegetation "similar to the *Betula-Juniperus* woodlands found around the Morrone Birkwoods today" (Huntley 1994, page 328). *Betula* macrofossils (fruit and catkins) form part of the assemblage throughout the Holocene, placing *Betula* in the immediate vicinity of the site, but it is unclear if *Betula* grew, as now, altitudinally above *Pinus,* or the two grew together. Above 100cm Huntley (1994) reports *Pinus* percentages of 30-40% TLP with *Betula* percentage of around 10% TLP; this could indicate separate of *Pinus* and *Betula* woodland or a denser *Pinus-Betula* canopy.

At both Loch Davan and Braeroddach Loch, *Pinus* pollen increases at the expense of *Betula* and Coryloid (Edwards 1978); Edwards does not regard separation of *Corylus* from *Myrica* as valid (Edwards 1983). *Betula* remains an important part of the assemblage but the gradual decline of *Betula* shows that *Pinus* replaced *Betula* in the landscape. Gradually *Quercus*, *Alnus* and *Ulmus* became more widespread, largely replacing *Pinus* by *c.* 4500 cal BP.

Rannoch Moor is similar to other areas with expansion of *Pinus* into *Betula-Corylus* woodland (Walker and Lowe 1981, Bridge *et al.* 1990). As this substitution occurred, *Corylus*/*Myrica* was already in decline, but *Betula* remained largely unchanged. There are oscillations between *Betula* or *Alnus* and *Pinus* during the Holocene, including almost complete disappearance of *Pinus* between *c.* 7300 cal BP and 5600 cal BP (Bridge *et al.* 1990) coinciding with the rise of *Alnus*. Its ability to colonise waterlogged soil means *Alnus* is more commonly regarded as a competitor to *Pinus* than to *Betula*. *Calluna* is present in all Bridge *et al.*'s (1990) sites from the early Holocene onward but became more important in the pollen assemblage after *Pinus* declined at *c.* 4600 cal BP.

2.6.8 Visual appearance of the trees and woodland

Pollen does not provide information concerning the appearance of trees, but a pollen sequence correlated with sub-fossil stumps or Coleoptera may show this. There are connections between climate stress and pollen production and climate stress and needle residence time (Section 2.2). Such variation in pollen production or needle residence would be apparent only in temporally differentiated sequences, such as annually varved lake sediments or modern samples. Inter-annual mixing of sediment is likely to mask all but very long changes.

The initial key to uncovering woodland appearance is resolving the relevant source area of pollen in the analysis (Section 2.6.2). If taxa location can be established ecological preferences of arboreal and ground flora can be used to infer the form of the woodland. Differentiation of Ericales is therefore very useful, separation within this family has improved inferences of woodland appearance.

Early studies, lacking clear inferences about the location of taxa in the surrounding area rely on the percentage representation and ecological preferences of identified species. At Loch Maree the initially dense canopy is maintained as a decline in *Pinus* is matched by an increase in *Betula* and *Alnus* (Birks 1972); increases in *Vaccinium* but not *Calluna*, reinforce the suggestion of a dense canopy.

Birks's (1970) study, based on an arboreal pollen sum rather than TLP, shows that the Abernethy Forest was dominated by *Pinus.* The other taxa present (*Betula, Juniperus* and *Populus*) occur today in 'rather open situations' (Birks 1970, page 840) and are suggested to have occupied gaps in the canopy. Birks and Mathewes (1978, page 475) agreed that *Pinus* woodland, with *Betula*, had an understory 'likely to be' dominated by dwarf shrubs in a relatively dense woodland. *Pinus* remains dominant until the present, but taxa indicating disturbance or canopy openings (*Plantago lanceolata*, Gramineae (Poaceae) and Ericales) become increasingly important.

O'Sullivan (1974a) introduces references to AP/NAP ratios in his analysis of the canopy in the mid to late Holocene. O'Sullivan reports that for pollen sums based on arboreal pollen counts (300 grains) and excluding mire taxa, *Pinus* percentages exceeding 60% are associated with closed canopy and 'semi-open' sites; with 40% or less indicating open sites (O'Sullivan 1974a). He does not set strict thresholds or indicate how these estimates are reached, but suggests that the canopy at Loch a'Chnuic was increasingly fragmented until *c.* 3800 cal BP. Brostrom *et al.* (2004), Sugita *et al.* (1999) and Soepboer and Lotter (2009) caution that AP/NAP ratios may tend to underestimate openness. However O'Sullivan's (1974a) conclusion, that forest around Loch a'Chnuic remained until historical times when clearance for timber use and grazing converted areas of the forest to heathland, probably remains valid.

McConnell and Legg (1994) refined the use of AP/NAP ratios by comparing the ratios of *Pinus* and *Calluna* to document the position of the tree-line on Creag Fhiaclach in the Southwest Cairngorms. In showing that forest cover may have extended above the present 648m OD, to 717m OD, they emphasise the spatial heterogeneity of pollen accumulation as an important driver of results. Binney (1997) also uses a single taxon, *Empetrum*, with a preference for very open sites and rather poorly dispersed pollen. The concept of using percentage of *Empetrum* to indicate openness has been introduced in Section 2.6.3. Using *Empetrum* percentage Binney (1997) found that woodland at Glean Einich and Beinn Dearg, was subject to fluctuations in canopy density throughout the mid to late Holocene.

Davies (2003a) argues that the consistent presence of *Calluna*, Cyperaceae, *Sphagnum* and *Potentilla* type pollen at the western end of Glen Affric in the mid-Holocene indicates presence of mire communities within open woodland.

Shaw (2006) considers AP/NAP ratios as useful in determining the nature of the woodland and refers to *Empetrum* indicating very local openings in the canopy. She also refers to palynological richness (after vad Odgaard 1999), to support continuation of mixed open woodland during increases of *Calluna* and AP decline, e.g. after *c.* 4000 cal BP in the PB core. This allows Shaw (2006) to show that at the western end of Glen Affric *Pinus* became sparser but remained present until at least *c.* 2000 cal BP.

Studies from Scandinavia and Finland demonstrate the relationship between density of woodland and pollen influx. Seppa and Hicks (2006) considered modern and past pollen accumulation rates across arctic tree-lines in Fenno-Scandia. Jensen *et al.* (2007) consider the modern pollen accumulation rate across ecotones in north western Norway and Hattestrand *et al.* (2008) sample modern pollen from discrete sites in Fennno-Scandia, Svalbard and Iceland.

Seppa and Hicks (2006) set out a simple model in which *Pinus* accumulations of more than 1500 grains cm^{-2} yr^{-1} are associated with dense pine-dominated forest; accumulations of between 1500 and 500 grains cm^{-2} yr^{-1} indicate sparse presence of

Pinus, and accumulations of less than 500 grains cm^{-2} yr^{-1} are associated with the absence of *Pinus*. Jensen *et al.* (2007) report a greater variety of vegetation patterns with associated *Pinus* pollen influxes. Inland locations with dense pine-dominated forest give accumulations in excess of 2000 grains cm^{-2} yr^{-1}, but open *Pinus* woodland in coastal locations give accumulation rates of just 200-400 grains cm^{-2} yr^{-1}. Mixed birch-pine forest inland is also associated with accumulations of 200-400 grains cm^{-2} yr^{-1} and sub-alpine birch forest is still more variable with accumulations of 240-720 grains cm^{-2} yr^{-1} and up to 2000 grains cm^{-2} yr^{-1} if two high pollen production years are included in the mean. The environments sampled by Hattestrand *et al.* (2008) also give wide variations in *Pinus* pollen accumulation rates. In pine forest median *Pinus* accumulations reach 4062 grains cm^{-2} yr^{-1} and in middle Boreal birch forest accumulations are higher still at 4748 grains cm^{-2} yr^{-1}. In birch-pine and birch woodland *Pinus* pollen accumulations are much lower with medians of 364 and 147 grains cm^{-2} yr^{-1} and median values for *Pinus* in areas without trees are as low as 52 grains cm^{-2} yr^{-1}.

2.6.9 Demise

The complete loss of *Pinus* from parts of the Scottish landscape has proved to be as hard to show as its colonisation and expansion. Local presence is demonstrated by stomata presence and their disappearance indicates very local disappearance of trees (Dunwiddie 1987, Froyd 2005). Once a closed canopy fragments there may still be sizable groups of trees, distal to the sample site, or scattered individuals close enough to contribute stomata to an assemblage. The former might show as a higher pollen count with no stomata, whilst the latter might give a low pollen count with stomata. Differentiation between these modes of growth may be possible with reference to light requirements of identified taxa (McConnell and Legg 1994, Binney 1997, Shaw 2006), or to pollen influx. Increases of taxa likely to be from extra-local sources may also help to define the likelihood of tree presence within an open landscape (Favre *et al.* 2008).

Disappearance of *Pinus* from the woodland environment is also problematic as even within a semi-open canopy extra-local input of pollen may be limited (Bunting *et al.* 2004). Fragmentation of closed canopy woodland to heath with scattered trees can be easily defined but in an open environment extra-local pollen becomes increasingly important (Fossit 1994a and b, Bunting 2003, Bunting *et al.* 2004), and disappearance of *Pinus* from the landscape less certain. The pioneering nature of *Pinus* (Section 2.2) means an apparent disappearance can be very rapidly reversed, especially in a peripheral area (Section 2.3).

In core areas, by definition, *Pinus* woodland tends to fragment rather than disappear. Around Loch Maree fragmentation began as early as *c.* 7400 cal BP (Birks 1972) and became more rapid around *c.* 4900 cal BP. *Pinus* percentages remain similar to the top of the core suggesting only minor changes after that. At Loch Clair, *Pinus* declined from *c.* 5400 cal BP (Pennington *et al.* 1972) and *Betula* became increasingly important. *Calluna* remained present, suggesting open *Betula-Pinus* woodland until the present day. The gradual decline in *Pinus* is accompanied by increases in taxa that ‘could all have formed part of the field communities in native pinewoods’ (Pennington *et al.* 1972, page 282). Although neither Birks (1972) nor Pennington *et al.* 1972) find that woodland fragmentation was caused by human impact, neither specifically state why woodland did fragment.

In west Glen Affric, *Pinus* began to decline at *c.* 4000 cal BP with woodland continuing to fragment until *c.* 2000 cal BP (Davies 2003a and b, Shaw 2006), by which time the valley consisted of the 'apparently monotonous treeless landscape' seen today (Davies 2003b, page 75). At Torran Beithe, Davies (2003a, page 47) suggests that climatic change is the 'primary cause of ecological change'. She also notes that low intensity human activity can have a disproportionate effect during woodland disequilibrium. Anthropogenic indicators are absent at Torran Beithe but present at Carnach Mor and Camban from before the earliest pine declines (*c.* 4840 cal BP). In east Glen Affric *Pinus* remained common until the present day (Froyd 2005). Shaw (2006) suggests that the westward decrease in *Pinus* abundance is linked to increasing rainfall, as wetter conditions inhibit seed maturation and germination (Section 2.2). However she is reluctant to separate wetter conditions from the lack of long term dominance in any particular area by *Pinus*, citing Pyatt (1994) in support of the maintenance of more resilient soil structure by broadleaved taxa under a broadleaved canopy. The preference by *Pinus* for bare un-compacted surfaces in order to germinate (Section 2.2) may mean that conditions under a broadleaved canopy inhibit the spread of *Pinus*.

In Speyside, Birks (1974) and O'Sullivan (1974a, 1976) regard *Pinus* and *Betula-Pinus* woodland as persisting until the present day (Section 2.3). But change associated with human activity takes place as early as *c.* 6300 cal BP in Abernethy (O'Sullivan 1974a), with sporadic appearances of ruderal taxa. Between *c.* 6300 and 3900 cal BP a series of peaks of several NAP types at Loch Garten suggest limited human activity. More intense woodland clearance and heathland formation takes place between *c.* 1400 and 800 cal BP, and leaves behind an altered woodland. O'Sullivan (1976) reports similar timescales and activity from Loch Pityoulish. At Loch A'Chnuic in the remoter parts of Abernethy Forest, woodland gradually turned to heath over a longer period, with intensive activity only during the 18th Century. At this time very rapid extraction of timber removed remaining woodland entirely. Woodland recovers from *c.* 1880 AD onwards. Gradual disappearance of much woodland around Loch Einich began as early as *c.* 4500 cal BP (Birks 1975). This is regarded as a natural effect, reinforced by use of the area for grazing and removal of trees for timber or fuel.

In core areas, woodland is subject to fragmentation from as early as *c.* 7500 cal BP; fragmentation is diachronous and is believed to have been earliest in the west (Tipping 1994, Huntley *et al.* 1997). Human activity is sometimes implicated in woodland fragmentation but is more often cited as reinforcing the effects of a maritime climate preferentially affecting *Pinus* dominated woodlands (Section 2.2 and previous page). Only in Speyside is human activity thought to initiate disintegration.

Tree-line studies often show disappearances from peripheral areas, which is of potential importance to the investigation into relationships between the sites in this study. At Loch Sionascaig, Inverpolly, *Pinus* woodland began to fragment at *c.* 4000 cal BP. Pennington *et al.* (1972) implicate human activity in this process, with reference to increases in *Plantago lanceolata* in the *Betula-Pinus* assemblage. Both *Betula* and *Pinus* disappeared by *c.* 1500 cal BP.

Binney (1997) showed that *Pinus* density was greatest at the lowest site, Dime Mor (270m), from *c.* 7700 to 5600 cal BP but became increasingly scattered from *c.* 5600-3600 cal BP. Open *Pinus* woodland with *Calluna* was the dominant vegetation after *c.* 3600 cal BP.

A small population, in constant flux, has remained on Rannoch Moor on “the extreme west of the area of Pine dominance in the Grampian mountains” (Walker and Lowe 1981, page 475). At the Rannoch and Corrour Stations and Kingshouse sites, *Pinus* disappeared by the mid-Holocene, probably as a result of increasingly wet conditions and competition from *Alnus* (Walker and Lowe 1981).

In the Howe of Cromar, Edwards (1978) found a *Pinus* maximum of up to 60% TLP between *c.* 6600 and 7300 cal BP, after which *Pinus* percentages decline. Edwards finds evidence of human presence in the Howe only after *c.* 3900 cal BP. Replacement of *Pinus* by *Betula*, *Alnus* and *Quercus* in a closed canopy suggests that cool damp conditions in the woodland prevented *Pinus* regeneration. This substitution of *Pinus* by others could indicate the retreat of *Pinus* westwards towards the core area.

Binney's (1997) sites in the Cairngorms are between 15 and 20km from Mar Lodge. Binney considers that evidence from Allt a'Phris Ghiubhais (500m), Carn a'Phris Ghiubhais (630m) and Lochan Odhar (700m) shows dense *Pinus* canopy until *c.* 7000 cal BP. Open woodland extends over all three sites until a rise in the tree-line after *c.* 6250 cal BP. The period of final canopy fragmentation to *Calluna* moorland, between *c.* 3650 and 4500 cal BP is linked with an abrupt transition to cooler, wetter conditions (Binney 1997, Anderson *et al.* 1998). Though human activity is not implicated in the disappearance of pine from Gleann Einich, pollen assemblages at the highest site, Moine Mhor (930m OD), suggest isolated *Pinus* stands between *c.* 3300 and 3100 cal BP. Binney speculates that this may relate to a high regional pollen signal or that the disappearance of pine from lower sites was not driven by climate. The high flat expanse of Moine Mhor is certainly not a likely site for human activity at any time. If pine was present there, climate changes are still likely to be implicated in its subsequent disappearance.

2.7 Other proxy data for past *Pinus* woodland

Other proxy data by which to assess past *Pinus* woodland have recently become available. Beetle assemblages, for example, can indicate types of woodland, health of woodland and presence of fire (Clark 2003). They can be used on their own (Whitehouse 2006) or in combination with other techniques e.g. pollen, to confirm, reject or inform about local woodland cover. Very recently Coleopteran assemblages have been used in the ongoing debate over the extent of openness in primary woodland (Whitehouse and Smith 2010).

2.8 Summary of Chapter 2, hypotheses and aims for the project

2.8.1 Woodland history

- The presence of *Pinus* in upper Deeside is as a result of favourable climate

The nature and history of pine woodland has been extensively investigated in many areas of Scotland, but upper Deeside has remained relatively understudied. The inaccessibility of the area may be a reason it has been overlooked by palaeoecologists, but this is an oversight because the area is not only an important area for pine woods, it is also an unusual area of the country, in the rain shadow of the western mountains, climatically more continental than anywhere else in Scotland.

Climate is important to the question of the persistence of *Pinus* woodland in different areas of Scotland. Despite being able to withstand low temperatures and drought, *Pinus* may be less able to tolerate the damp cool conditions of a maritime climate. If *Pinus* woodland in the eastern Cairngorms can be shown to behave similarly to other areas of Scotland, this would reduce the likelihood of *Pinus* ecology being principally climatically controlled.

2.8.2 Core areas of woodland

- *Pinus* became established in upper Deeside early, was present throughout the Holocene, and is therefore a core area of *Pinus* woodland

Areas with early colonisation and persistent presence of *Pinus* woodland, usually until the present day, are referred to as 'core areas'. Core woodland areas in Scotland include the northwest (e.g. Loch Maree and Loch Clair), Glen Affric and Speyside. Dumfries and Galloway are excluded from the core areas for Scottish *Pinus*, representing rather shorter *Pinus* residence, probably of a northward outlier of southern *Pinus*. Rannoch Moor is a peripheral area, with rather sporadic *Pinus* residence. The sites investigated at Beinn Dearg (Binney 1997) are also best described as peripheral areas although they have a very early population, dated to *c.* 8400 cal BP. Caithness is not included as a core area, but represents Scottish populations moving northward for a limited time period, another peripheral area of *Pinus* colonisation.

2.8.3 First Appearance and woodland expansion

- A time difference between first appearance of pine stomata and increases in *Pinus* pollen percentage is typical of the colonisation of an area by *Pinus*
- The time difference between first appearance of pine stomata and increases in pollen percentage is explicable with reference to *Pinus* ecology including competition and interaction with arboreal and non-arboreal taxa

Pollen and stomatal evidence from core areas show the first appearance of *Pinus* to be between *c.* 9600 and 7480 cal BP, with woodland expansion from *c.* 9200 cal BP. In east Glen Affric, Froyd (2005) identifies a lag between the first appearance of trees and the increase in pollen abundance that is not apparent in west Glen Affric (Davies 2003 a and b). With no other pollen and stomata studies detailing the appearance of *Pinus* it is unclear whether this lag is typical of *Pinus* colonisation or an aspect, e.g. taphonomic or taxonomic, of Froyd's study. By replicating the techniques used in Glen Affric, this study will explore whether such a lag is a typical facet of *Pinus* ecology, and, if it is, provide reasons why this occurs.

2.8.4 Woodland density

- *Pinus* canopy density has been continually high in upper Deeside

Most core areas of *Pinus* in Scotland have been designated as such by reference to high pollen percentages and the link between canopy density and persistent presence. A consideration of canopy density including *Pinus* will form an important part of this study. Scandinavian studies linking pollen influx with canopy density have not yet been utilised in the Scottish context, but provide a useful comparator to pollen percentage, AP/NAP ratios and ratios between single species and *Pinus*.

2.8.5 Woodland diversity and competitive interactions

- *Pinus* is only able to maintain presence within a diverse arboreal assemblage

Extant woodland in Glen Affric, Speyside and northwest Scotland is relatively diverse, despite *Betula*, *Quercus* and *Alnus* potentially providing competition to *Pinus*. The modern woodlands of Mar Lodge and upper Deeside seem unusually species-poor in comparison; whether this has always been the case in upper Deeside has important implications for the extent to which *Pinus* is able to dominate the landscape.

- Presence of non-arboreal taxa, especially Ericales, hinders *Pinus* regeneration

Arboreal taxa are not the only competition for *Pinus*; field layer vegetation including Ericales and *Sphagnum*, may also have competitive interactions with *Pinus.* Improvements in taxonomic separation and better understanding of the relevant source areas for Ericales pollen may make it possible to identify of these competitive relationships in Mar Lodge.

Establishing the diversity of the assemblage in Mar Lodge will at first be by identification of the pollen taxa, but palynological richness will also be calculated. The only area available as a comparator in the Scottish context is Glen Affric, a second area with a rarefaction record will help develop the use of this technique.

2.8.6 Use of recently developed palynological methods

Improvements in pollen taxonomy in the last 30 years in themselves justify a replication of Pears' (1968) tree-line study. This has been partly addressed by Binney (1997), who utilised some of the developments in taxonomy, the understanding of pollen behaviour and the statistical basis of pollen analysis in a tree-line analysis. However the questions set out in Section 2.5 remain unanswered for a valley floor location in upper Deeside. There is no stomatal history from the eastern Cairngorms, and the most recent developments in pollen and charcoal taxonomy and taphonomy have not been tested. These techniques provide the basis for evaluating the establishment, expansion, vigour, density and possible decline of *Pinus* populations in Mar Lodge.

2.8.7 Timescales

The aim of many recent palaeoecological studies is to sub-sample at ecological timescales. This is desirable in this study, as fine resolution sampling may reveal short period correlations between taxa, as well as relationships such as masting and needle residence times of *Pinus* and other rapid changes in vegetation and sediment history.

2.8.8 Other proxies for woodland

A single recent proxy study of the palaeoecology of *Pinus* is available from Mar Lodge. Clark’s (2003) study of Coleoptera, from Geldie Lodge, provides information of the form and health of *Pinus* not available in a pollen record. Comparison of the Coleopteran assemblage with a pollen assemblage is novel to the area and unusual in the Scottish Holocene. It is hoped to link specific details revealed by Coleoptera, for example, indicators of deadwood or wetlands, with *Pinus* pollen and stomata in the palynological assemblage.

2.8.9 Anthropogenic activity

- *Pinus* woodland in upper Deeside was affected by anthropogenic activity

People have been implicated in the destruction of woodland, including pine woodland, elsewhere in Scotland. Edwards (1978) detailed firm evidence of human activity from lower Deeside, but as with other aspects of the history of Mar Lodge early human impact is not known. Recent archaeological discoveries suggest Mesolithic hunters were present in the Mar Lodge area, including the vicinity of White Bridge and Geldie Lodge. Identifying the impact, if any, of these people, from pollen and charcoal, would give rare evidence of the early activities of people in an inland situation. Both early and subsequent activity by people in the area may be implicated in changes to the woodlands themselves.

3 Research area, research strategy, sites and methods

3.1 The Cairngorms and Mar Lodge Estate, introduction and context

3.1.1 The Cairngorm National Park

The Cairngorm Mountains form the centrepiece of the Cairngorm National Park in the Grampian Mountains in Eastern Scotland (Figure 2.1, Figure 3.1). The National Park was created in 2007 but the Cairngorms have been recognised as an internationally important area for nature conservation for many years (Watson 1996). In some ways the Cairngorms are similar to other parts of the Grampian Mountains, but they also have distinctive ecologies, biological and physical systems, as well as human histories. Mar Lodge Estate includes a large part of the south eastern Cairngorms.

In this section a brief consideration of the geology, geography and modern climate of the Cairngorms can be found in Sections 3.1.2, 3.1.3 and 3.1.4. A description of the modern boundaries and character of the modern Mar Lodge area, precedes a brief introduction to the history of the Estate (Section 3.1.5). The extent of known settlement and human activity in the Mar Lodge area is discussed in Section 3.1.6, and is followed by general aspects of soil (Section 3.1.7) and vegetation (Section 3.1.8).

Section 3.2 details the criteria for selection of sites. Section 3.3 locates and describes each site. Descriptions include basin features and morphology, local vegetation, previous work in the area where appropriate, and a consideration of the extent to which the site satisfies the aims of the study. This chapter is completed by details of the laboratory analyses carried out on the sampled cores. Sites in the Cairngorm area mentioned in this and Chapter 2 are shown in Figure 3.1.

Figure 3.1 The Cairngorm Mountains (for location within Scotland see Figure 2.2) Numbers indicate locations mentioned in text: 1. Doire Bhraghad, 2. White Bridge, 3. Geldie Lodge, all from this study; 4. Loch Einich (Binney 1997); 5a Sgor Mor, b Moine Mhor, c Glen Eidart, (Pears 1968); 6. The Morrone Birkwoods, (Huntley 1994); (7) Lochan Oir, (Huntley 1997); 8. Loch Einich, (Birks 1972); 9. Loch a'Chnuic, (O'Sullivan 1974); 10. Loch Pityoulish, (O'Sullivan 1976). Loch Garten (O'Sullivan 1974) and Abernethy Forest (Birks 1970 and Birks and Mathewes 1978) are just off the top of the map above location 10. 11. Craeg Fhiaclach**, (**McConnel and Legg 1994); 12. Glen Geusachan (Sissons 1979, Everest and Kubik 2006, Golledge *et al*. 2008, Golledge 2010). 13 and 14. Peat deposits on Invercauld and Balmoral Estates, mentioned in Section 7.5.2. (Ordnance Survey 2011).

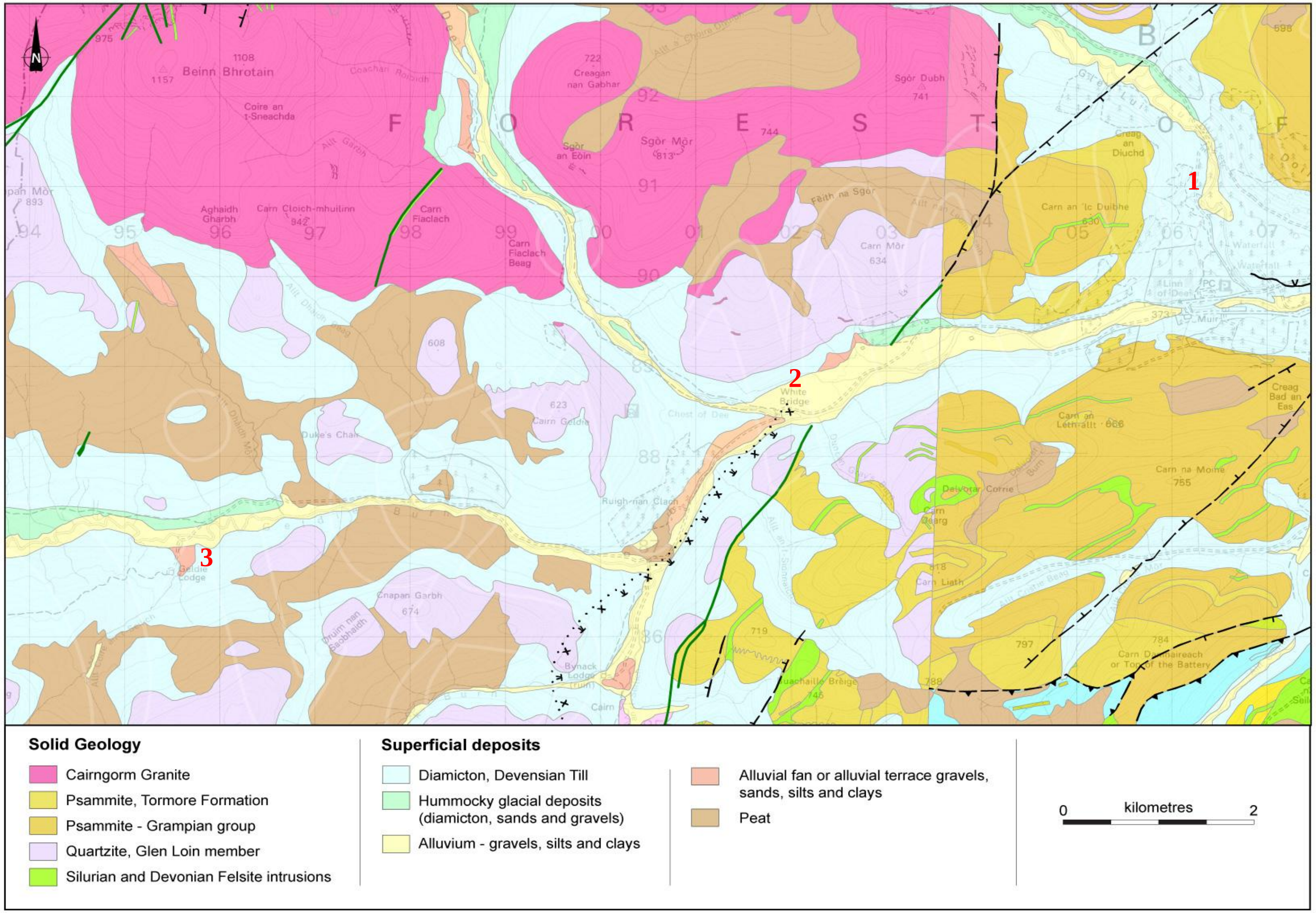


Figure 3.2. Mar Lodge Estate surface geology (Ordnance Survey 2010). Numbered Locations as Figure 3.1.

3.1.2 Solid and superficial geology

Surface geology, including superficial and solid outcrop, is shown in Figure 3.3. The central massif of the Cairngorms, Cairngorm (Brown) Granite, is one of a series of granitic plutons emplaced toward the end of the Caledonian Orogeny some 400 million years ago (Watson 1984). In the Eastern Grampians granite also outcrops north of the River Dee between Braemar and Ballater, around Lochnagar and north of Blair Athol. Although the current distinctive appearance owes much to the present glacial-interglacial regime, the orientation of the valleys probably dates from very soon after the emplacement of the granite. The major valleys, Glen Dee, Lairig Ghru, Glen Derry etc, are probably orientated along hydrothermal vents channelling volatile fluids away from the magma during and shortly after intrusion (Gillespie 2003, MacDonald 2003, Thomas *et al*. 2004). During intrusion gases including carbon dioxide and sulfur dioxide mix with water to form acidic, superheated fluids, chemically weathering the susceptible feldspar component of the granite, chemically weathering the rock while it is still 2-3km below the surface.

Metamorphic contact between granite and Psammite (Tormore Formation), lies to the north of all three of the core sites in Mar Lodge. The Tormore Psammites are part of the Dalradian Supergroup found between the Highland Boundary and Great Glen Faults. They are largely impermeable rocks with low porosity, physically hard and chemically impervious, giving thin acidic soils with little mineral content. A minor exception to this is the area near Braemar underlying the Morrone Birkwoods (Figure 3.1, location 6), where the rocks are Limestones or calcareous schist.

Superficial deposits of fluvial, glacio-fluvial and glacial material cover much of the area. Glen Lui is underlain principally by till (boulder clay) with some glacio-fluvial sands and gravels, while the bottoms of Glen Dee and Glen Geldie are covered in glacio-fluvial deposits. Till in the area is derived from glaciation during the last maximum of the Devensian, the Dimlington Stadial (see below, Geography of the Cairngorms), but glacio-fluvial deposits are of this age and later, from the Loch Lomond Stadial (Younger Dryas). Fluvial deposits are of Holocene age.

3.1.3 The geography of the Cairngorms

The Cairngorms are the largest continuous area of high ground in Britain (Watt and Jones 1948). The main plateau includes five areas higher than 1200m OD: Cairngorm, Cairn Lochan, Beinn MacDuibh, Braigh Riabhaich and Carn an t'Sabhail. Only Cairngorm and Cairn Lochan are wholly outside the Mar Lodge Estate. To the east of this very high ground, there is a similarly sized expanse of land almost entirely above 500m OD and typically over 800m OD. In addition to being, for Britain, very high, this area is very remote with few tracks even along the deeply incised valleys.

The distinctive appearance of the terrain originates from a combination of the solid geology and glacial processes. Although the current glacial regime began perhaps 2.4 million years ago, the form of deep steep sided valleys and high plateaux without dramatic peaks may derive partly from much earlier periods (Section 3.1.2). Tors on the plateaux were uncovered and maintained by ice and frost shattering, but probably also originate from intense chemical weathering shortly after intrusion of granite. Valleys such as Glen Dee, Glen Derry and Glen Lui owe some of their current form to partial deflection of ice sheets moving east north east, during the last glacial maximum. Ice overriding the summits was thin, cold and therefore slower moving or static (Hall 1996), compared to valley ice. Philips *et al.* (2006) used cosmogenic dating to show that the oldest rock surfaces on the summit plateaux predate the last glacial maximum.

The numerous corries surrounding the plateaux owe their existence to shorter stadials, where the build up of ice was within local hollows or on the plateaux. The main phase of corrie formation in the Cairngorms was at the end of the Dimlington Stadial (Philips *et al.* 2006). Ice build up during the Loch Lomond Stadial (Younger Dryas) has been the subject of considerable debate. Sugden's (1970) interpretation of glaciation was criticised by Sissons (1979), who considered that glaciers were less extensive. Everest and Kubik (2006) agreed with limits of the glacier occupying Glen Geusachan (Figures 3.1 and 3.4, location 12) set by Sissons (1979) but cosmogenic ^{10}Beryllium dating showed boulders there dated from the end of the Devensian Stadial, prior to the Late-glacial Interstadial. Everest and Kubik (2006) posit a Late-glacial standstill of glaciers and disappearance of valley glaciers from the Cairngorms before the Loch Lomond Stadial.

Glen Geusachan is by far the largest of the 17 glaciers identified, mapped and grouped chronologically by Sissons (1979). Cosmogenic dating of Glen Geusachan boulders implies that all of Sissons' glaciers date from before the Loch Lomond Stadial, leaving the valleys of Glen Lui, Glen Dee and Glen Geldie free of active ice by *c.* 16.5 ka BP. At what point the valleys were totally free of ice is less certain, as considerable areas of hummocky glacial deposits are present in all three valleys (Figure 3.2). Hummocky glacial deposits were linked with decay of static ice (Sissons 1979). Bennett and Boulton (1993) showed that hummocky deposits relate to active decay of glaciers at the end of the Loch Lomond Stadial in western Scotland. Whether this conclusion can be extended to encompass other Late-glacial glaciers in eastern Scotland is unclear, leaving the possibility of all three sites retaining a static ice cover sometime into the Late-glacial Interstadial. Ice may have accumulated on the summit plateaux during the Loch Lomond Stadial but it did not advance into the valleys. It is thought that during the ‘little ice age’ (*c*. 1550-1850 AD), permanent glacier ice did not develop in the Cairngorms (Rapson 1985).

3.1.4 Present-day climate

The high plateaux are high enough in the present climate to maintain isolated snowfields as late as August and extensive enough to generate climatic differences between east and west of the massif. According to Conrad’s index of continentality the central Cairngorm is one of the few areas of Scotland not classed as maritime (Crawford 1997) and differences between east and west are discernible.
Braemar is the nearest weather station to Mar Lodge and is the oldest in the Cairngorm area (McClatchey 1996), with data available from 1855. Data from 1959 is available on-line (UK Meteorological Office). This large dataset shows that Braemar has a relatively cool climate, partly due to its altitude, 339m OD. Braemar and Grantown on Spey and other settlements surrounding the Cairngorms record their lowest temperatures during temperature inversions. The lowest temperature recorded in Britain is from Braemar in 1982, -27.2^{o}C. Grantown’s temperature was recorded as -26.8^{o}C, while the monitoring station on Cairngorm summit recorded -12.6^{o}C (McClatchey 1996). Braemar can experience air frost in any month. For the 51 years of online data average temperature in January was 1.1^{o}C and in July, 13.4^{o}C. Meteorological observations from the west side of the Cairngorms are less readily available. Aviemore (229m OD) has half hourly observations available, but only from 1982. The next nearest long datasets are from Dalwhinnie (339m OD), 30km south of Aviemore and from Ardtalnaig (130m OD) on Loch Tay.

McClatchey (1996) has compiled data for Aviemore and Braemar sampling just under four years of data between 1985 and 1988. This period was slightly colder in Braemar than the 51 year average, with average temperature in January being 0.6°C and in July, 12.7°C, while Aviemore's averages were 1.1°C and 13.5°C in January and July respectively. Once adjusted for differences in altitude, there is little difference between the temperatures of the two places.

Figure 3.3 shows average rainfall in Scotland. Apart from the mountain summits, the general trend of a drier east and a wetter west is clear. Also very clear are the valleys of the Spey and the Dee (arrowed in red and black respectively), which form narrow fingers of drier land around the mountains. Despite finding large local variations, McClatchey (1996) concluded that the east Cairngorms typically receive 680mm and the west Cairngorms 780mm of precipitation each year.

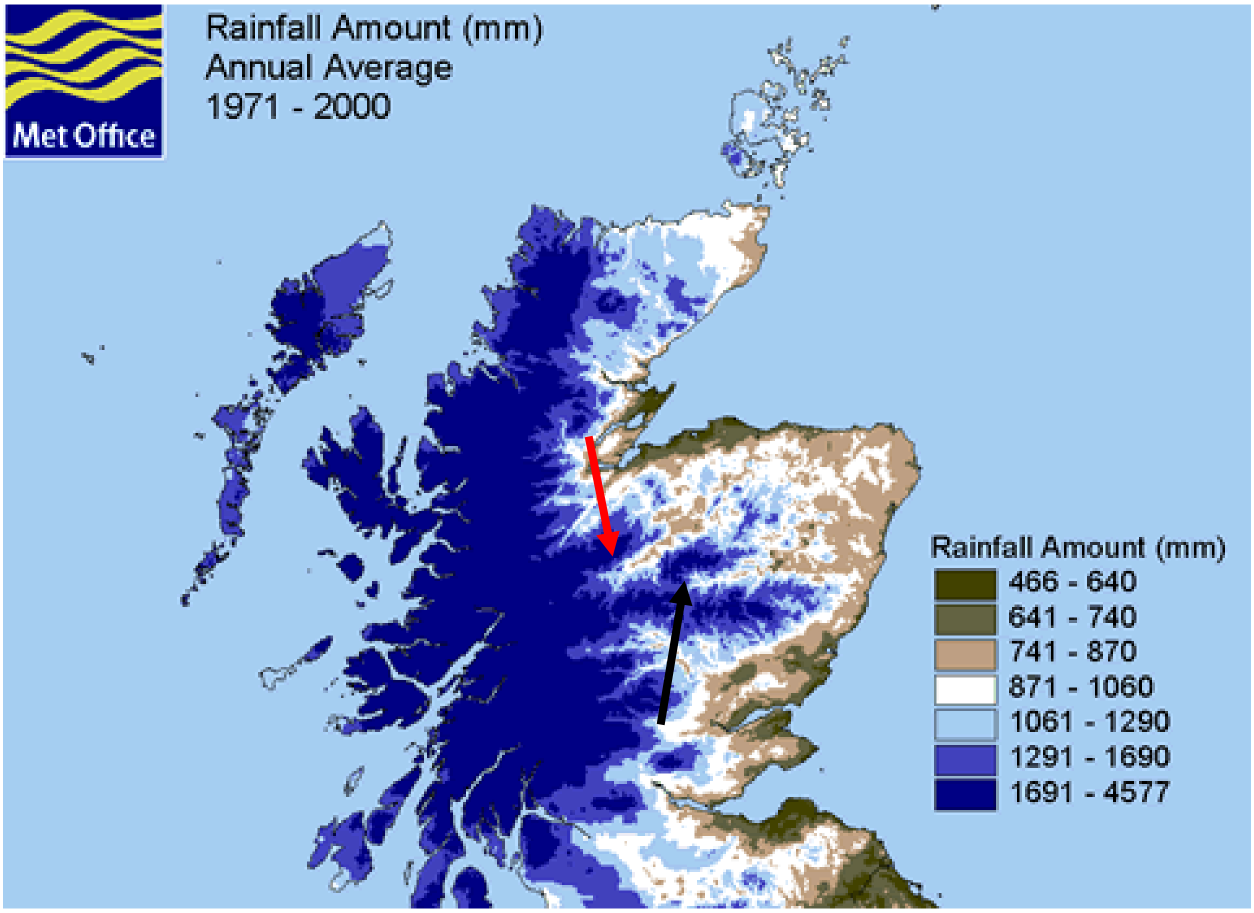


Figure 3.3 Scotland, average annual rainfall. Black arrow shows position of Mar Lodge Estate in upper Deeside, the eastern extension of relatively low precipitation along the Dee valley is also obvious. According to these figures Doire Bhraghad and White Bridge are within this dry extension but Geldie Lodge is slightly wetter. Speyside is the drier extension arrowed in red. (United Kingdom Meteorological office 2011).

3.1.5 The Estate of Mar

The Mar Lodge Estate now covers approximately 29000 hectares of the southeast Cairngorms including all of Glen Derry, Glen Lui, Glen Luibeg, Glen Quoich and Glen Geldie (Figure 3.4). The Upper Dee Valley and Lairigh Ghru (Figure 3.4, locations 19 and 20) is the traditional drove route between the southern Cairngorms and Speyside. The watershed between the Bynack Burn (Figure 3.1) and Glen Tilt on the southern boundary links Braemar to Blair Atholl and the Tay Valley. The watershed between the Geldie Burn and the River Feshie does not seem to have been used as a route way, possibly because of the steep descent into Glen Feshie. The River Feshie has probably captured the upper 10km or so of the Geldie Burn.

All ground within the estate lies above 300m and most is above 400m. The estate extends onto and is bounded by the Cairngorm plateaux summits of Beinn MacDuibh (1309m), Derry Cairngorm (1155m), Braigh Riabhaich (1291m) and Carn Toul (1251m). It contains *Pinus* woodland in the valleys of Glen Dee, Glen Lui, Glen Derry and Glen Quoich (Figure 3.4). There are also areas of pine heath, open moorland and heath. The summits are dominated by arctic-alpine vegetation.

The modern Mar Lodge Estate is the most westerly part of the Earldom of Mar. The origin of the Estate goes back to at least 1014 (Dixon and Fraser 2007) when it included nearly all of Deeside and much of the upper Don valley. The semi-autonomous status of the estate meant that relatively little colonisation by Norman families took place and the direct line of pre-Norman Earls of Mar continued until the early 15th Century. In the 14th Century Mar was favoured by royalty (Robert II) as a

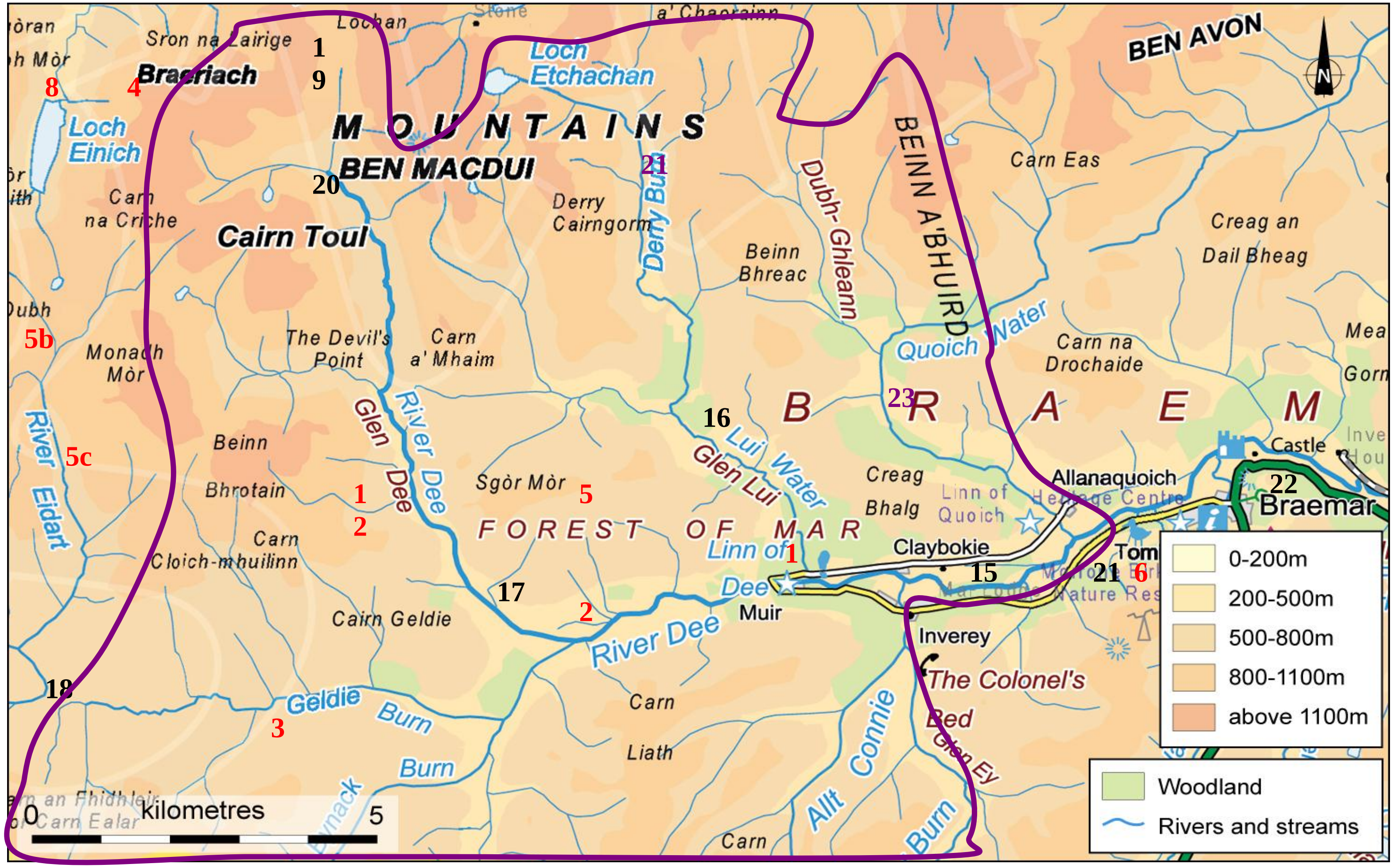


Figure 3.4 The Mar Lodge Estate. Boundary of Mar Lodge Estate indicated in purple. Numbers in red show site locations as in Figure 3.1. Other locations are in black: 15. Mar Lodge; 16. Glen Luibeg; 17. Chest of Dee; 18. Headwaters of River Feshie and Geldie Burn; 19. Lairig Ghru; 20. Uppermost Glen Dee; 21. Crathie; 22. Braemar. (Ordnance Survey 2010).

hunting retreat, and following the end of the direct line, James I (1424-1437) took control of the Earldom (Ross 2005). Lands to the east, including Strathdon and The Howe of Cromar (Figure 2.1, location 2) had already been relinquished. James II (1437-1460) retained control of Mar, using the area as a run for ‘wild’ horses. In 1565 the Crown granted control of the Estate to the Erskine family, who continued to maintain it as a hunting estate. The importance of deer hunting in the area is clear from a description of a hunt in 1618, in which 500-600 beaters gathered animals to a suitable spot, enabling the gentlemen to make the kill with a variety of bows and guns (Dixon *et al*. 1995).

It is likely that the only agricultural activity west of Inverey in the historic period before the 17th Century was cattle grazing. During the 17th and 18th Centuries the complicated system of tenants and sub-tenants led to settlement and farming west of the Linn of Dee (Figure 3.4, near location 1) and in Glen Lui (Figure 3.4, locations 1 and 26). In Glen Lui this settlement was short lived as the then Estate owners, Lords Grange and Dun, found logging to be more profitable and evicted the inhabitants.

Timber extraction remained important to the Estate throughout the 18th Century, with sawmills in both Glen Lui and Glen Quoich. Logging in the Glens was unlikely to have involved replanting; a contemporary description by Cordiner in 1780 reports many thousands of stumps on the valley sides. During the late 18th and early 19th Centuries, valleys including Glen Geldie, Glen Bynack and Glen Dee (Figure 3.4) were let, by the Estate, to local sheep farmers and to shepherds from Glen Shee, Coupar Angus and Rothiemurchus. Sheep farming was also a relatively short-lived activity and deer management soon dominated the Estate again. In the late 19th century deer populations were probably very high as the Estate reared deer to sell to stock the woods of Rothiemurchus on Speyside. During this resurgence of deer hunting any remaining hill grazing by the inhabitants of Inverey came to an end.

At this time Mar Estate still included Glen Ey and Glen Christie south of Inverey (Figure 3.4). The present form of the Estate came into being in the 20th Century, as areas south and east of Inverey remained as Mar Estate, with the main Estate becoming known as Mar Lodge Estate. Deer management continued to be the most important economic activity, notwithstanding several grandiose plans by owners in the mid 20th century to increase tourism. These included plans to establish a ski resort at Beinn a'Bhuird (Figure 3.4), at the head of Glen Quoich, of which only a hill track to within about 200m of the summit now remains.

The National Trust for Scotland (NTS) took over management of the Mar Lodge Estate in 1995. NTS have maintained Mar Lodge as a hunting estate, but have altered the focus of management to a more 'traditional' system. In practise this involves removing or not replacing some artificial structures, including fences and some bridges, and downgrading paths to limit vehicular access. Fences removed include those that had protected some patches of woodland from grazing by deer. This makes another aim, reduction of deer grazing pressure on the estate, important as management of woodland moves towards natural regeneration.

3.1.6 Settlement

Work designed to diminish the impact of paths and tracks in Glen Dee and Glen Geldie has uncovered several finds of Mesolithic flints (Ballin 2004, Clarke 2007). These finds are close to two of the sites investigated in detail in this study, White Bridge and Geldie Lodge (Figures 3.1 and 3.4, locations 2 and 3) and make Mar Lodge an important source of inland finds of that age. However within the Mar

Lodge area there are no identified settlements of any age until the late medieval period. The height above sea level makes this one of the least hospitable parts of the country; it was probably never heavily populated. Lack of finds may also relate to relatively limited investigation and peat may have grown over early settlement sites. The movement of river channels during flood events may have destroyed evidence and made early settlement temporary. However there are areas that are likely to have been attractive to people, perhaps because they provide safety in inaccessibility.

The wealth of settlement and other evidence of Neolithic and Bronze Age activity in the adjacent Don valley suggests that Deeside was also known to early people. Gannon *et al.* (2007) regard the Howe of Alford and the Howe of Cromar (Figure 2.1, location 2) as occupying similar positions at the exits of the Don and Dee rivers from their relatively narrow upland valleys. While Gannon *et al.* (2007) note that no Bronze Age stone circles have been found west of the Howe of Alford and suggest that a similar case could exist on Deeside, west of the Howe of Cromar, they concede that many of the monumental finds in Donside were as a result of intensive farming in the 19th Century.

Whatever the cause, in Lower Deeside, apart from a probably seasonal camp near the Howe of Cromar (Edwards 1978), there are few examples of settlement until the Iron Age. Edwards (1978) suggests that Neolithic people preferred less heavily wooded areas away from the valley bottoms. Patterns of monuments and artefact finds in the lower Dee valley seem to indicate that there was little change in the areas of occupation between the Neolithic and Bronze Ages (Gannon *et al.* 2007). This situation changes during the Iron Age as a series of archaeological structures, including crannogs, field systems and hollow ways show people to have been occupying the land.

The first record of permanent settlement in upper Deeside is from Braemar (Figure 3.4, location 22) at around 1000 AD; however permanent settlement is first recorded west of Inverey only in the late 17th Century. By this time the area is clearly already subject to more than the requirements of subsistence farmers. In late medieval times ‘the Forester’, with powers rather greater than today’s estate factor, carried out the administration of the Forest of Mar, on behalf of the landowner. By 1700 tenants and sub-tenants of ‘the Forester’, were living and farming in Glen Dee west of the Linn of Dee, and in Glen Lui and Glen Ey. It is unclear how many people were affected by the evictions from Glen Lui near the third site examined in detail in this study, Doire Bhraghad (Figure 3.1, 3.4, location 1) in 1726, (Section 3.1.5).

One of the main results of improvements to the Estate during the 18th Century was the demise of the traditional system of farming. Townships in Glen Lui had already been cleared, but restrictions were introduced on grazing, wood collection and on building utilising wood. This led to declines in the numbers of inhabitants, and an eastward movement of permanent settlement. The population of the parishes of Braemar and Crathie (Figure 3.4, locations 21 and 22) fell from 2671 in 1755 to 1876 in 1801. It seems reasonable to suppose that population was higher still prior to 1755, bearing in mind the large numbers involved in the hunt in 1618.

During the 19th Century, as deer became increasingly important to the Estate economy, sheep farms were gradually abandoned. In the mid 19th Century tenants relinquished farms that had been converted from townships in the Dee valley. Hunting Lodges including Geldie Lodge and Derry Lodge were erected in the late 19th Century but were probably no longer in use by the early 20th Century. These lodges would have had permanent residents to serve hunting parties. These people are likely to have been the last permanent inhabitants of the Glens west of Inverey.

3.1.7 Soils within Mar Lodge Estate

Generally poor soils in the Mar Lodge Estate, made the area unnattractive for early settlement. Much of the soil on the valley floor around Doire Bhraghad and White Bridge is featureless, amorphous organic sediment with quartz grit, often less than 10cm thick. There are some drier thicker soils around the former townships and sheep farms, west of the Linn of Dee. However even these settlements (e.g. Dubrach, Tonnagaoithe, Figure 3.11) do not exhibit clear evidence of the usual Highland response to thin infertile soils, the ridge and furrow. Alluvial material is present near all three sites, but is not necessarily of use for cultivation, being dominated by the wide shallow, flood prone rivers. One of the smallest areas of superficial deposits, on river terraces (Figure 3.2), may have been more attractive as a location for cultivation. Soils on the terraces may not be appreciably better than elsewhere, but do have the advantage of being well drained and raised sufficiently above the rivers to avoid flooding.

The largest area of alluvial terrace deposits is near White Bridge, though this is just outside the likely pollen source area for the site (Figure 3.12). The lower valley sides consist mainly of podsols which, though freely drained are typically on steep ground, can be thin and are rarely suitable for cultivation. Deeper soils on flatter areas tend to be wet, and merge with larger peat spreads as altitude increases. Lower summits are typically covered with deep peat whilst the high summits have very thin regolith, with very little organic material. In Glens Lui, Luibeg, Derry, Dee and Quoich there are many slightly thicker peat sequences (typically 40-90cm) which share a distinctive stratigraphy (Figure 3.5). It comprises a basal unit of amorphous peat with little or no identifiable plant material, overlain by a very dark brown or black layer typically 5cm thick. The surface layer consists of lighter coloured peat with a much higher proportion of identifiable plant material, especially sedges.

3.1.8 Modern vegetation

Pinus sylvestris woodland occupies a relatively limited area in Mar Lodge. The main areas of 'natural' woodland are within Glen Dee, from the Linn of Dee eastward, Glen Lui, Glen Derry and Glen Quoich (Figure 3.1, 3.4). Woodland is very varied with dense woodland in parts of Glen Derry, Glen Lui and Glen Dee interspersed with open woodland. Figure 2.1 encapsulates the form of the woodland in the glens; scattered trees with a heath and grass understory are separated by heath with some grass. There are occasional birch (*Betula*) and rowan (*Sorbus*) present within the pine woodland. *Sorbus* seems to be particularly associated with apparently recently planted woodland. There are also dense plantations of pine and non-native conifers in Glen Dee and Glen Lui.

Figure 3.5 Typical stratigraphy from Glen Lui and Glen Dee, still in a 1m long 2.5cm wide Eijkelkamp corer. Very dark brown to black peat is separated from light brown sedge peat by a thin layer of black material, including charcoal.

Grassland is often more common around river banks and surrounding old (abandoned) settlements. Apart from these areas heaths are dominant up to highest summits. Above about 1000m OD heaths give way to an arctic flora including lichens and mosses with some flowering herbs. More detailed descriptions of vegetation surrounding each core site are given in Figures 3.9, 3.14 and 3.20.

3.2 Site selection

The initial focus of the study was on the valley floor because this is where patches of extant *Pinus* woodland are found (Figure 3.4), a context in which survival from the early Holocene was hypothesised (Section 2.3). In preferring to use valley floor sites it is important to recall that though they can be perceived as lowland areas, in Mar Lodge the valley floor is never much lower than 400m. One of the aims of the study, the investigation of stand-scale changes to woodland on the valley floor, requires sites reflecting mainly local pollen source areas. Pollen assemblages from large basins will include pollen recruited from valley sides because valleys are relatively narrow, so the palynological distinction between valley and hillside vegetation may be blurred. Small hollows are therefore desirable (Section 2.3), but blanket peat can offer relatively local pollen recruitment. Even these locations can include pollen recruited from valley sides if they are close to the edge of the valley.

Full Holocene peat sequences, to establish the presence of *Pinus* from the early Holocene, should also be as thick as possible to allow highly resolved temporal analyses. Sequences with no stratigraphic complications, for example, truncations, should be avoided. Hiatuses in deposition are not always obvious, but are more likely when there are abrupt changes in sedimentation.

The discovery of late Mesolithic flints at, and west of, the Chest of Dee (Figure 3.11 and 3.13) and in Glen Geldie (Figure 3.16) gave the possibility of associating vegetation change with known Mesolithic presence. Identification of a suitable site in the vicinity of these finds added a further constraint on site choice.

In practice thick peat sequences are not common on the valley floor in the Mar Lodge area, perhaps reflecting the relatively dry climate. The search for suitable peat sequences in the Mar Lodge area, including Glens Lui, Luibeg, Derry, Quoich and Dee, as far east as Allanaquoich (Figure 3.4), located the relatively small, deep basins at Doire Bhraghad and White Bridge. Geldie Lodge is higher and more distant from extant woodland, and is a thick blanket peat rather than a small basin, the subject of a previous study by Clark (2003). In addition to the opportunity of identifying human impact, this site also offers a comparison between a pollen study and a Coleopteran study. The extent to which each of the sites conforms to selection criteria is discussed below.

3.3 Description of sites

3.3.1. Doire Bhraghad, NGR NO064906, 400m OD

The general location of Doire Bhraghad is shown in Figure 3.1, 3.4, and in local detail in Figure 3.7. The basin itself is shown in Figure 3.6 a and b. Doire Bhraghad is located in Glen Lui. The mouth of Glen Lui joins Glen Dee at the Linn of Dee, and the head of the valley is connected *via* a low glacial breach to uppermost Glen Dee. Cairngorm Granite underlies the head of Glen Lui, but the Doire Bhraghad basin lies outside the granite pluton and is underlain by the Tormore Psammite Formation of the Dalradian Supergroup (Figure 3.2). Much of Glen Lui is underlain by Devensian till of unknown thickness, but Doire Bhraghad itself lies in an area of glacio-fluvial sand and gravel. The basin is thought to be a kettle hole and lies about 400m from the western side of the valley in a section of Glen Lui which runs north to south. The Lui Water is separated from Doire Bhraghad by about 250m of dry ground,

Figure 3.6a (above) Doire Bhraghad basin, looking west, April 2007 shows shallow water on the east side of the basin. **Figure 3.6b** (below) detail of core site, August 2009 shows shallower water typical of late summer. The mire surface is usually driest in late May and June, over the last few years water has started to pond during July and August.

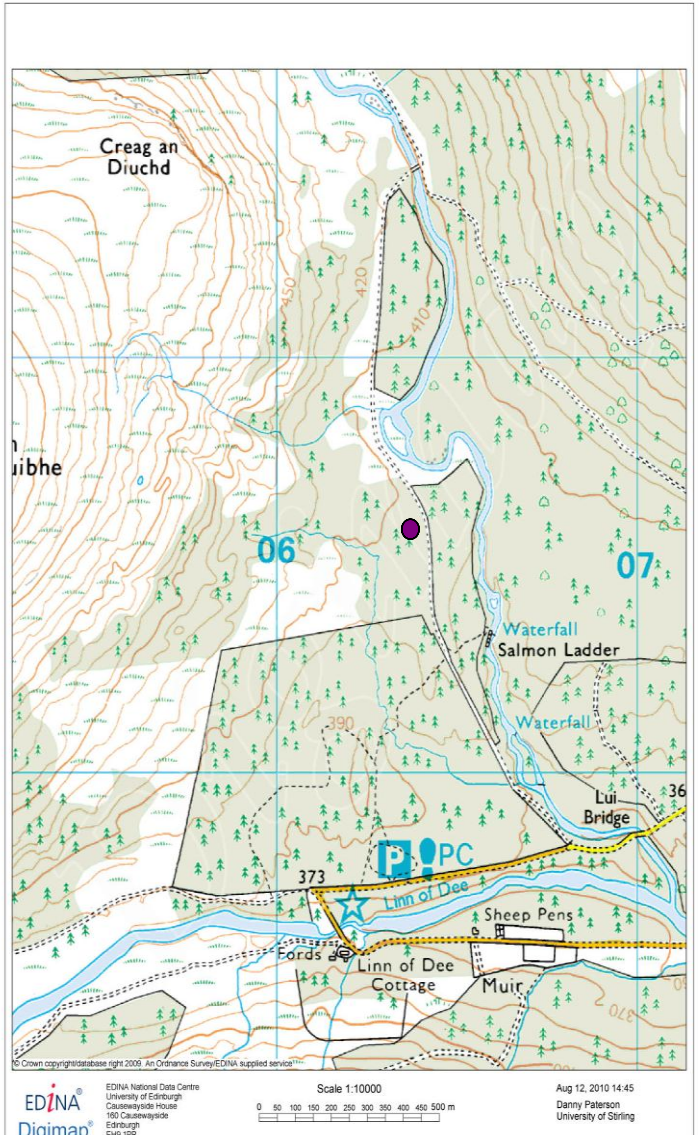


Figure 3.7 Doire Bhraghad core site, purple spot, in a north south orientated section of Glen Lui. The nearest major contour is miss-labelled and should be 400m OD.

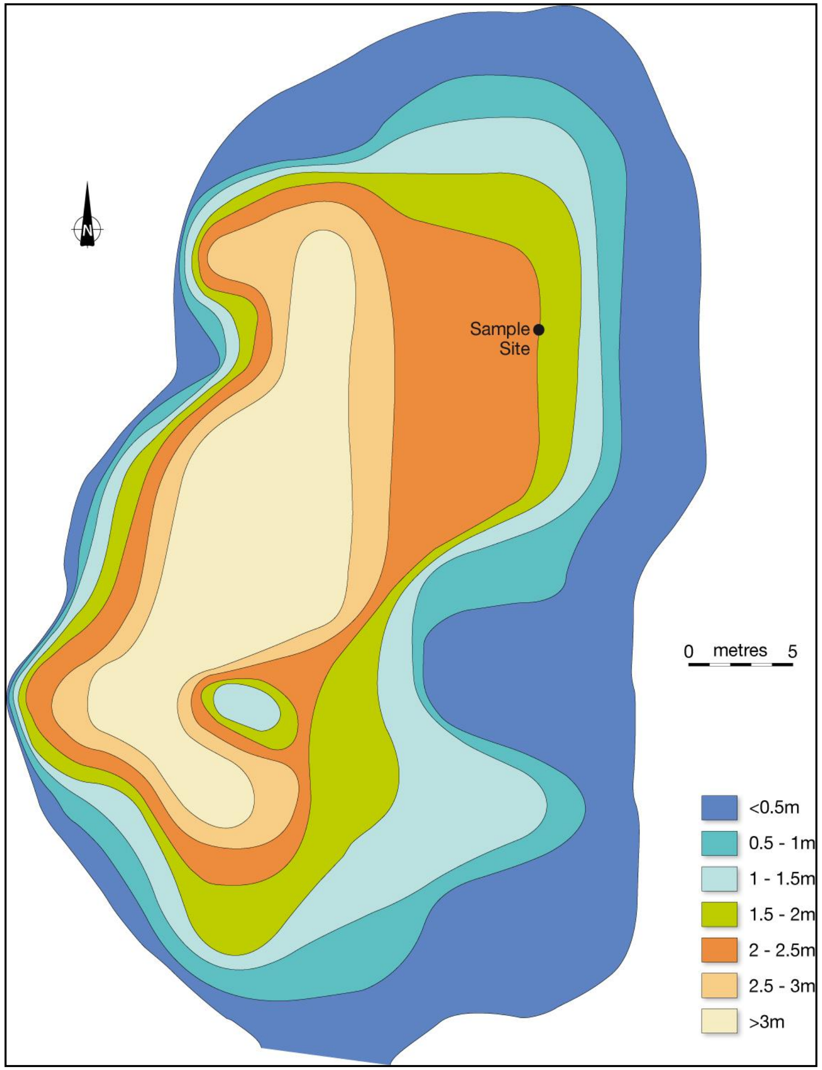


Figure 3.8 Doire Bhraghad basin morphology.

up to 10m above the level of the river. The modern river bed is therefore slightly lower than the bottom of the mire.

The confluence of the Lui Water and River Dee is approximately 1km to the south of Doire Bhraghad. Together the valleys of the Lui and Dee form a roughly equilateral triangle. The Dee occupies one side; the Doire Bhraghad basin is towards the apex of the triangle. To the north of the basin the valley floor is flat and dry, lying up to 10m above the Lui Water. To the south the ground slopes gently towards the confluence of the rivers. The surrounding hills are up to 600m OD which may shelter the basin from prevailing winds; it is certainly the case that this part of Glen Lui tends to be less windy than the east-west trending valley of the Dee (author's own observation during fieldwork). The closer western slopes are steeper than the valley sides on the eastern side of the valley, and today feature occasional *Pinus* within a *Calluna* heath. Doire Bhraghad takes its name from the extensive *Pinus* dominated woodland on the shallower eastern slopes.

Basin morphology was established in August 2008 and May 2009, using a 1m long, 2.5cm wide, Eijkelkamp gouge corer. Depth and stratigraphy were recorded at 2m intervals across the basin in east-west transects 5m apart. Peat depth within the basin is shown in Figure 3.8. The basin slopes above the mire surface are asymmetrical, continuing the form shown by the peat in-filled section. The eastern and northern edges of the basin are steeper than the western edge; the southern side of the basin is level with the peat surface outside the basin. Ground surrounding the basin on the east, west and north is almost flat. There are no streams flowing into the basin, but there may be movement of water out of it southward either as dissolute surface flow or perhaps as ground water. To the south a small stream drains the hillside to the west towards the Linn of Dee through a series of surface pools.

As can be seen in Figure 3.6, the mire surface is now differentiated between a relatively dry area and a much wetter substrate, with the drier part up to 70cm higher. Vegetation on the mire surface includes two mature *Pinus* individuals, surrounded by *Calluna*, *Vaccinium* and *Sphagnum*. The deepest parts of the basin (Figure 3.8) are to the left of the extant pine trees growing on the surface of the mire (Figure 3.6). This part of the basin is crossed by (sub-fossil?) roots of *Pinus* and has three *Pinus* stumps. The core position is on the edge of the lower wetter section of the mire (Figure 3.6). During winter this part of the basin consists of shallow (up to 5cm deep) water (obvious in Figure 3.6); this dries out during the summer. Cyperaceae, Poaceae and *Sphagnum* grow on the margins of this section (Figure 3.6b).

Figure 3.9 shows the National Vegetation Classes for the area around Doire Bhraghad. NVC lists the west side of the Lui Water, around Doire Bhraghad as mire, with *Pinus* woodland on the eastern side of the river. The mire classification includes *Calluna vulgaris-Vaccinium myrtillus* heath (H12) and *Erica tetralix-Sphagnum compactum* wet heath (M16), within these are scattered *Pinus,* typically mature and veteran individuals. Southwards, towards the Linn of Dee, the gently sloping, rather wet, ground has occasionally dense patches of *Pinus* with some *Betula* and occasional *Sorbus aucuparia.* This area is fenced and is probably planted. A generally sparse understory includes *Erica tetralix, Calluna vulgaris*, Cyperaceae, Poaceae and ferns. To the north and west (upper Glen Lui) scattered *Pinus* woodland with *Calluna* gives way to *Calluna* heath.

The Doire Bhraghad mire is the deepest basin on the valley floor found in the Mar Lodge area and has the thickest sequence, suggesting a full Holocene sequence. Though the stratigraphy has very clear changes, it had the potential for high temporal

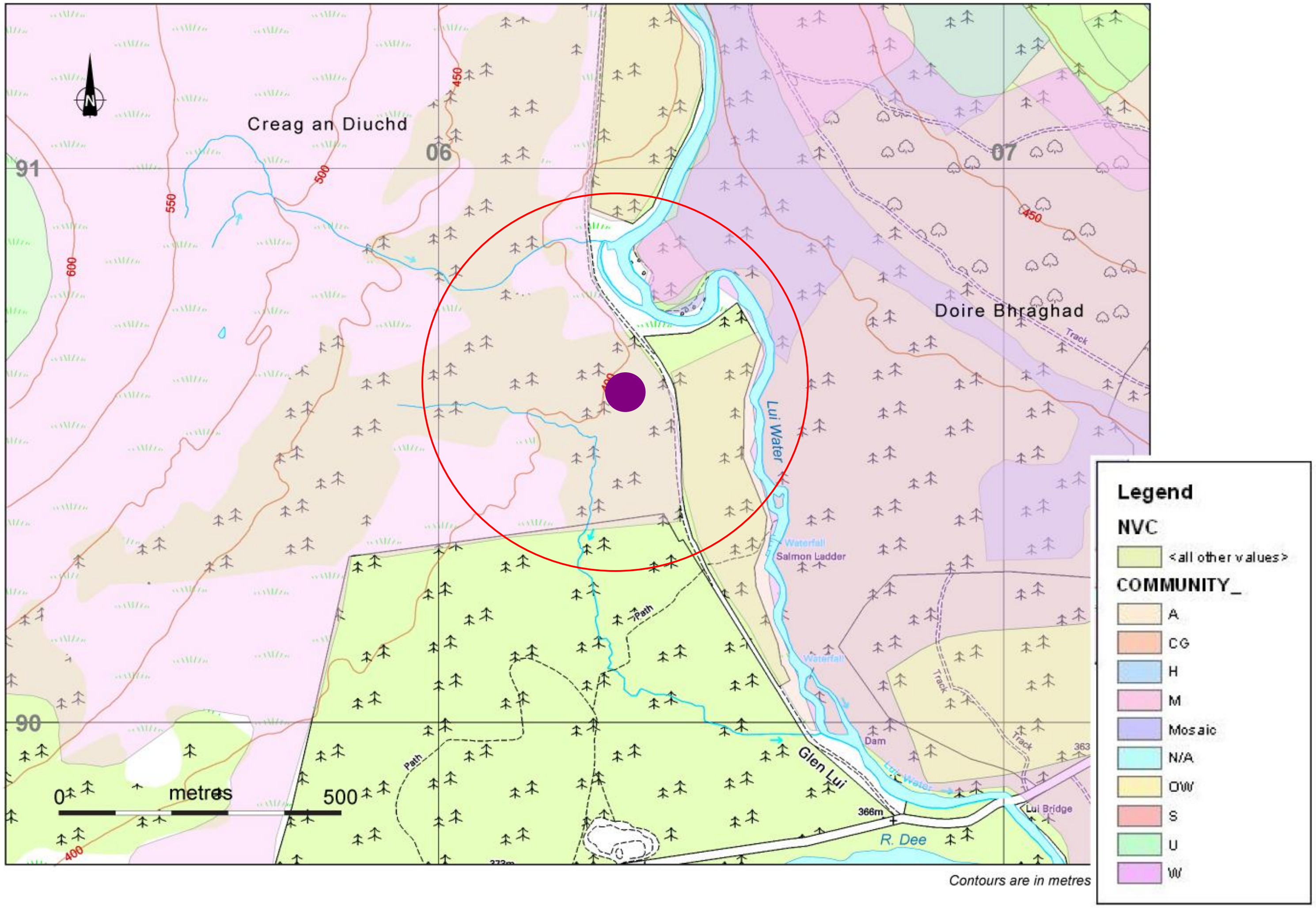


Figure 3.9 National vegetation classification near Doire Bhraghad core site (purple spot) courtesy of Scottish Natural Heritage, red circle indicates the likely maximum relevant source area for arboreal pollen. Key to Legend A- aquatic, CG- calcicolous grassland, H- heath; M- mire; NA- not available, OW- open woodland, S- swamp and tall herb fen, U- calcifuge grassland and montane communities, W- woodland and scrub. Vegetation classification is incomplete in this area, in particular the large parrelogram, bounded by fencing, to south of the core site is not available, difficulty with map colouring meant this area appears uncoloured on the map not green-blue as shown in the key. This area consists of occasionally dense patches of *Pinus* with some *Betula* and occasional *Sorbus aucuparia*.

resolution analyses. The basin is slightly larger than ideal, but nonetheless pollen recruitment is principally from the valley floor. There are no inflowing streams to the basin, and it is separated from any influence from the main river. The maximum RSAP for arboreal pollen is shown in Figure 3.9 as between 300 and 400 metres, but this will have been lower during periods of closed canopy woodland. The basin is approximately 400m from the valley slopes (Figure 3.7 and 3.9), beyond the probable RSAP of most arboreal taxa. More poorly dispersed pollen is likely to have a pollen source area much smaller than that depicted.

The 1.92m deep core was sampled using a 1.0m long, 5.0cm diameter Russian peat corer in November 2002. The corer cannot sample the lowermost 9cm of a deposit due to its nose cone. At Doire Bhraghad it was thought that this basal sediment was not significant.

3.3.2 White Bridge, NGR NO019887, 400m OD

The White Bridge site is located on the north side of the River Dee, 4km west of the Linn of Dee (Figures 3.1, 3.4 and 3.11). The valley lies beyond the Cairngorm granite pluton and is underlain by Tormore Psammite; superficial deposits of alluvial silts, sands and gravels cover the bedrock on the valley floor (Figure 3.2). Aerial photographs of the area reveal the valley floor to be a maze of superficial surface features associated with fluvial action (Figure 3.13). The core is from peat in a relatively long and narrow basin, an abandoned channel of the River Dee.

The mire surrounding the core site is bounded to the north by a dry river terrace about 2m above the mire surface, and to the south by a lower terrace (Figure 3.10, 3.13), both pre-date accumulation of the sampled peat. The higher terrace is approximately 50m wide, covered by thin (approximately 10cm) mineral soil and

Figure 3.10 The abandoned river channel near White Bridge, looking north east toward unnamed plantation. Purple spot indicates core site. The image is taken from the lower southern terrace, the edge of the higher dry terrace runs from front left to the middle distance.

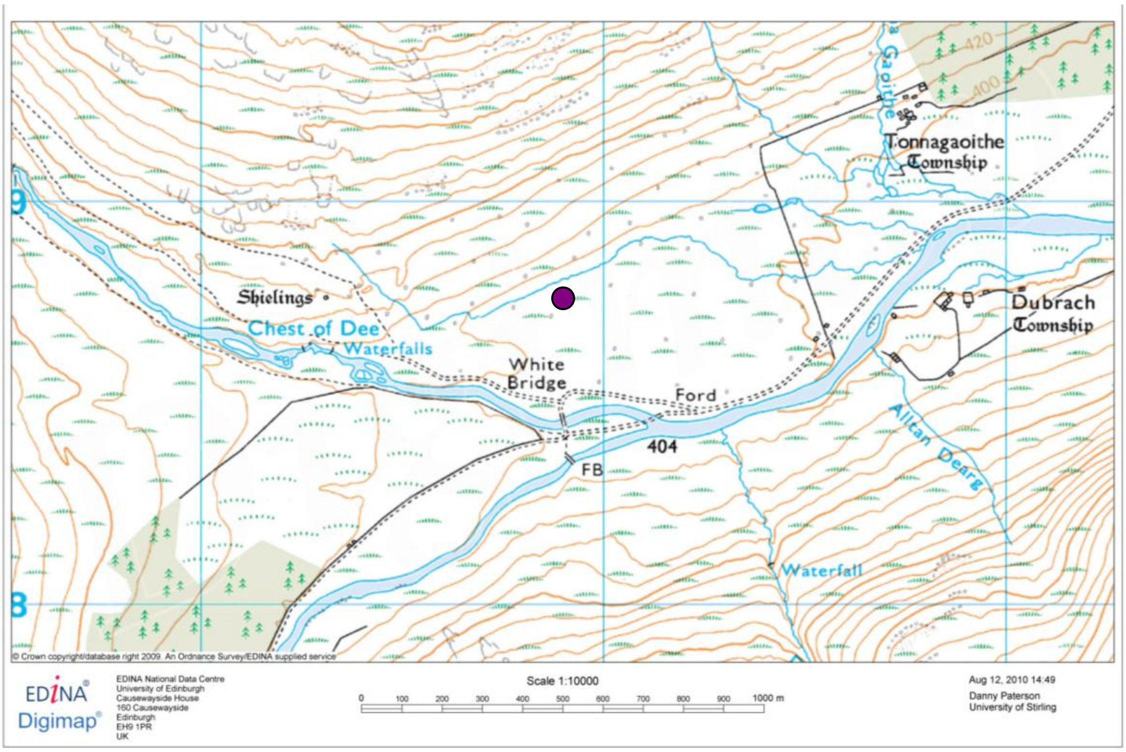


Figure 3.11 White Bridge core site, location (purple spot) within upper Glen Dee. The purple spot marks the core site. Mesolithic flints were discovered at the Chest of Dee.

strewn with large (up to 1.5m diameter) boulders. These are thought to be flood deposits related to an earlier phase of valley floor formation (Tipping *pers. comm.*). The terrace is bounded to the northwest by a small stream draining the northern valley side. To the south, between the palaeochannel and the River Dee, lower terraces are less than 1m above the sampled channel with a substrate of thin peat (around 20-40cm) with a few small boulders amongst shallow pools.

Eijkelkamp gouge survey to establish basin morphology (Figure 3.12) was carried out from November to February 2003-4. Depth and stratigraphy were recorded at 1m intervals along north west to south east transects at 10m intervals: note the distortions in length and width in Figure 3.13. The channel narrows upstream (south west) of the sample site and the peat also thins upstream, finally blocked by either bedrock or a plug of fluvial sediment about 150m from the coring site. The base of the sequence is at approximately the same height as the present river channel.

Figure 3.14 shows National Vegetation Classes for the White Bridge area. The whole area of the valley bottom surrounding the core site consists of *Trichophorum cespitosum-Erica tetralix* wet heath (M15). Vegetation on the channel surface itself includes rather larger proportions of Cyperaceae and *Sphagnum* with *Erica tetralix* and some *Calluna vulgaris*. Grass and sedges dominate vegetation adjacent to the modern river and around ruined settlements. The nearest trees are in a plantation of *Pinus* called Ruigh-nan Clach, just under 1km to the southwest (south west corner, Figure 3.11), and *Pinus* and *Picea abies* in an unnamed plantation 1km to the north east (centre left in Figure 3.10, north east corner, Figure 3.11). There are a few *Betula* trees at the Chest of Dee (Figure 3.11, 3.13) just under 1km to the west.

The transition from heath to mire on the northern side of the valley is at the base of the break in slope. This overlaps with the RSAP for the White Bridge site

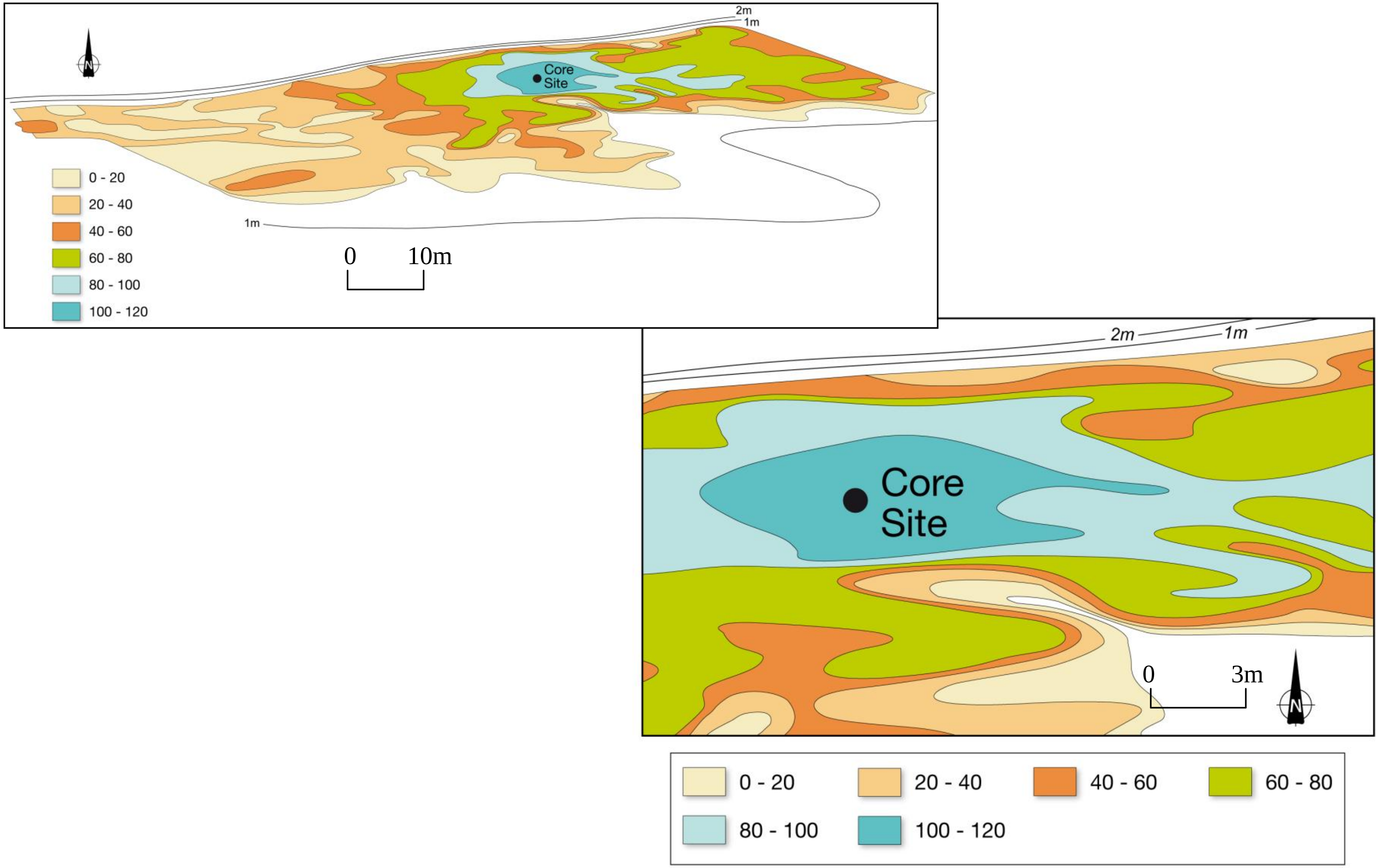


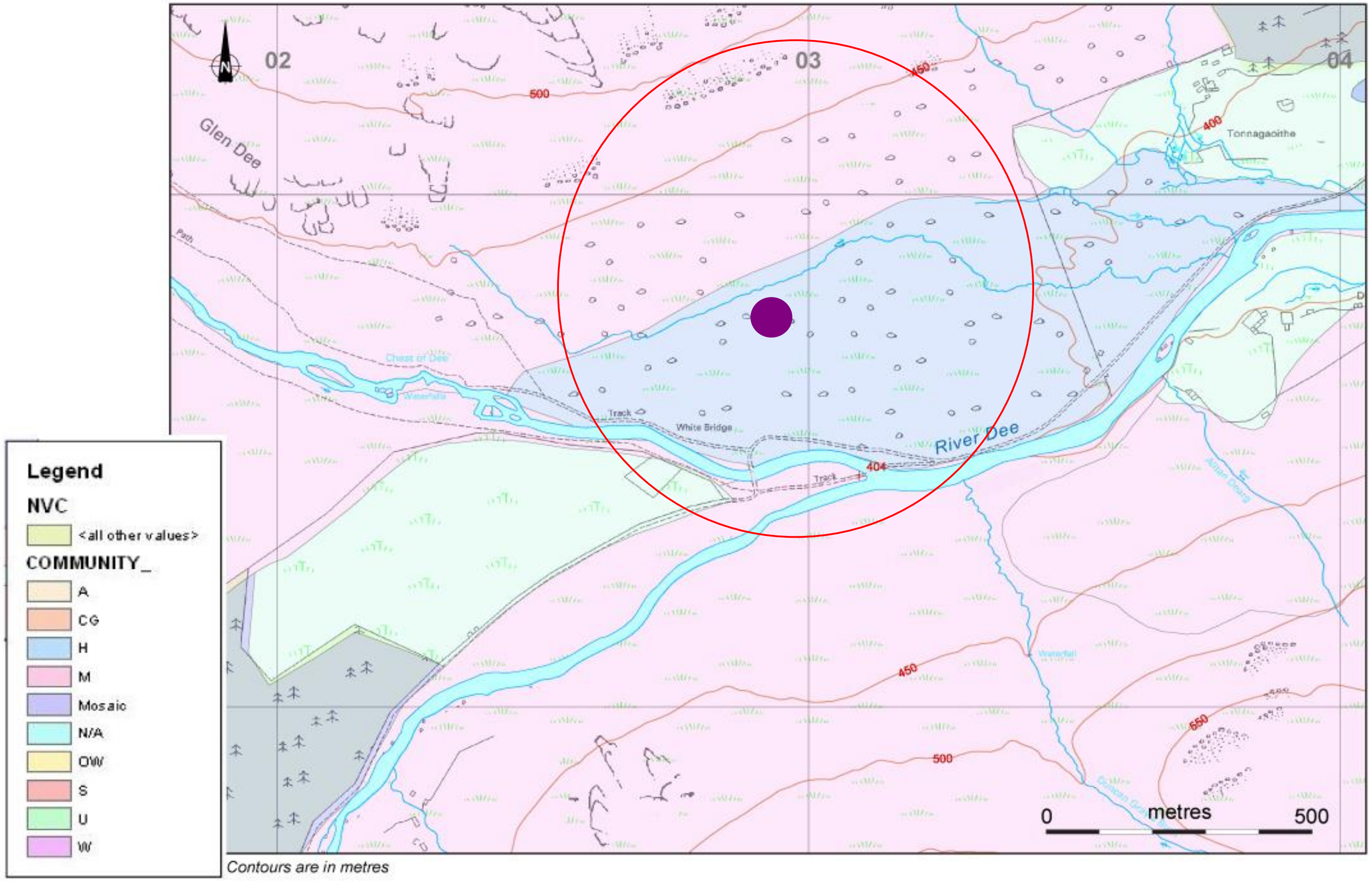
Figure 3.12a (top) White Bridge basin morphology showing the extended palaeochannel area. **Figure 12b** (bottom) Detail of the palaeochannel surrounding the core site itself.

(Figure 3.14), meaning that pollen recruitment to the site may include pollen from distal sources, particularly from arboreal taxa growing on the valley sides. The RSAP for White Bridge also overlaps with an area of montane grassland, on alluvial fan and terrace deposits (Figure 3.3). Pollen from vegetation growing on both these areas is more likely to feature in the White Bridge assemblage during periods of open canopy or open heath.

White Bridge is the shortest sequence in this study but is important in the context of landscape change due to its close proximity to several dense scatters of Mesolithic flints (Ballin 2004, Clarke 2007). There is more recent evidence of human settlement from several sites between the Linn of Dee and White Bridge. There are also the remains of shielings to the west of White Bridge above the River Dee and the remains of permanent settlements south of White Bridge in the Geldie Valley. The flint finds were the first suggesting that human activity in the area dates back to the Mesolithic period. The thinness of the peat is the principle disadvantage of the White Bridge sequence, but it is easily the thickest peat to be found in this part of Glen Dee. There are clear changes in sediment stratigraphy, and the location of the channel within about 200m of the steep valley side allows the possibility of pollen recruitment from above the valley floor, but the presence of the dry terrace to the north prevents direct runoff or sediment accumulation from the valley side. The palaeochannel is now protected from the influence of the river in its modern channel.

The bog was sampled using a Russian corer as at Doire Bhraghad. The full sequence of 114.5cm was sampled into two cores, 0-100cm and 14.5-114.5cm, with additional cores taken to provide sediment for radiocarbon analysis. The lowermost 9cm was not sampled.

Figure 3.13 Aerial photograph of the valley floor at White Bridge. The valley widens downstream of series of low waterfalls at the Chest of Dee. The main channel of the modern River Dee runs along the bottom of this image, the edge of the dry terrace to the north of the core site visible in Figure 3.11 is also clear on hers, showing as a darker line. The series of parallel diagonal lines running northwest to southeast are thought to be related to former river flow earlier in the Holocene.



Contours are in metres

Figure 3.14 National vegetation classification around White Bridge core site (purple spot) courtesy of Scottish Natural Heritage. Key to Legend A- aquatic, CG- calcicolous grassland, H- heath; M- mire; NA- not available, OW- open woodland, S- swamp and tall herb fen, U- calcifuge grassland and montane communities, W- woodland and scrub. Vegetation classification is complete in the White Bridge area. The red circle indicates the likely maximum relevant source are for arboreal pollen.

Figure 3.15 Looking south west across Glen Geldie. The River in the foreground is the Geldie Burn. Geldie Lodge is the light coloured building is in the middle distance to the left of the core site. The hill in the background, approximately 5km distant, An Sgarsoch, 1006m OD is not shown on location maps. The sampling point by Clark (2003) and this study is shown by the purple spot, red arrow indicates the position of the second peat section in Figure 3.14.

3.3.3 Geldie Lodge, NGR NO957870, 510m OD

The Geldie Lodge site is located around 300m north east of Geldie Lodge, an abandoned hunting lodge above Allt Coire an t-Seilich, a tributary of the Geldie Burn (Figures 3.15, 3.16). The Geldie valley runs west-east, linking the southeast Cairngorms (Deeside) and the southwest Cairngorms (Glen Feshie) (Figure 3.1 and 3.4). The solid geology consists of Tormore Psammite, covered by superficial deposits of till, alluvial gravels, sands and silts, and coarse alluvial fan material underlying the Allt Coire an t-Seilich (Figure 3.2). The blanket peat from which the core is taken covers the broad, relatively shallow valley (Figure 3.15), overlying and mostly obscuring the alluvial deposits. Geldie Lodge is approximately 5km east of the watershed between the Geldie Burn and the River Feshie.

Allt Coire an t-Seilich is eroding into the north and eastern edges of the blanket peat. The sample site lies about 1.5m metres behind the vertical peat face forming a river cliff on the outside of an active meander. The face is around 1.4m high, except where stream action has undermined *in situ* tree stumps, leading to collapse of the peat (Figure 3.18 and 3.19). The peat behind the face is blanket mire with shallow *Sphagnum*-rich pools, sloping gently up to the south, above the alluvial fan. To the west blanket peat is bounded by the Allt Coire an t-Seilich. Along the Geldie Burn lateral erosion by the river has truncated the peat (Figures 3.18 and 3.19).

Basin morphology (Figure 3.17) was established in May 2009 using a 1m long, 2.5cm wide, Eijkelkamp gouge corer. Depth and stratigraphy were sampled every 2m along 2m wide transects orientated northwest-southeast, parallel to the river. Peat south east of the coring site becomes thicker, reaching a maximum depth of 2.1-1.8m (Figure 3.17) before thinning gradually up the hillside toward An Sgarsoch (Figure 3.16). To the east peat becomes thicker, (2-3m deep), covering a large almost

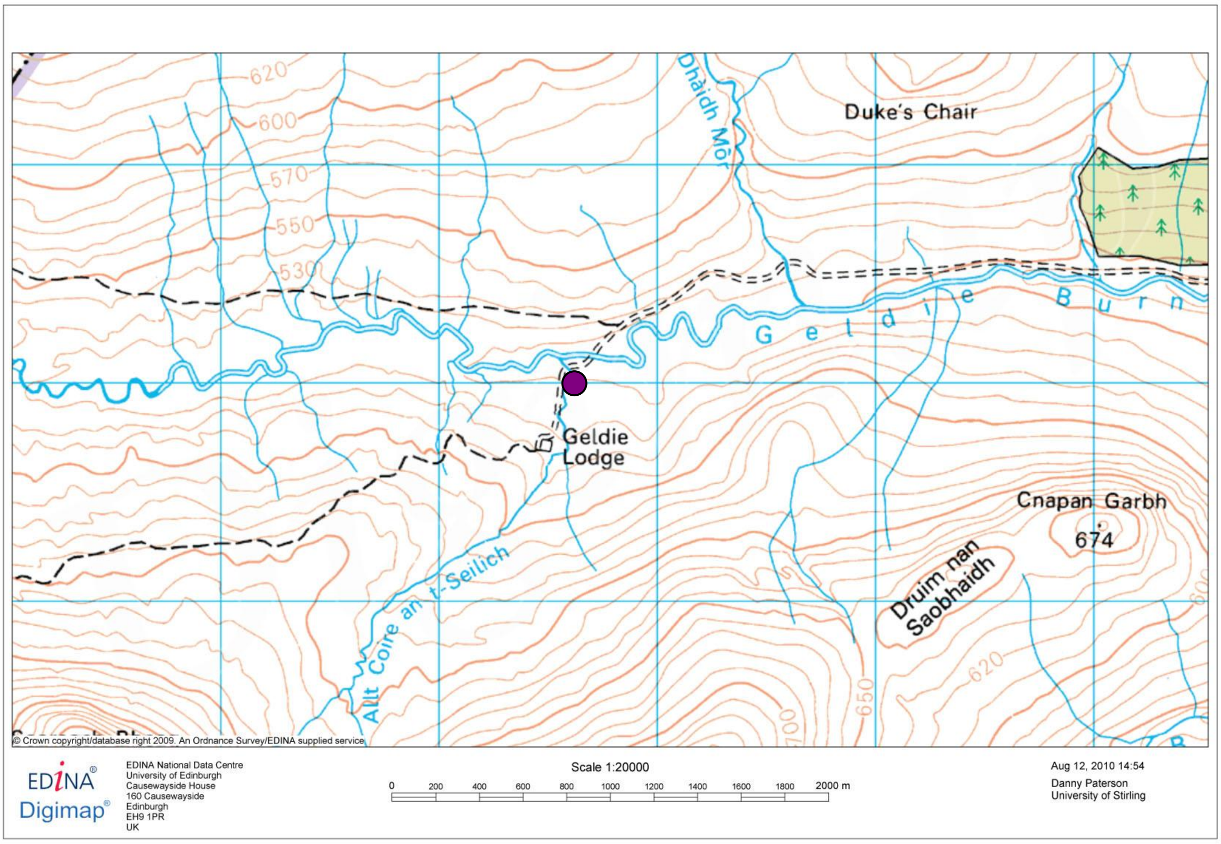


Figure 3.16 Location of Geldie Lodge core site (purple spot) between Geldie Lodge and Geldie Burn. Actual location indicated by a purple spot.

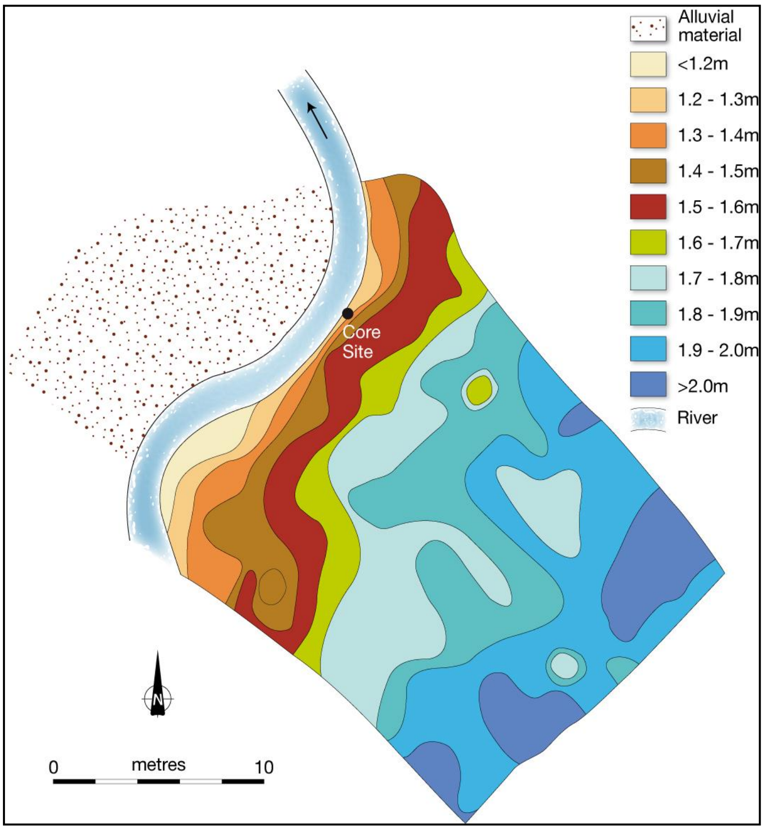


Figure 3.17 Geldie Lodge basin morphology

Figure 3.18 (left). Looking south east at the exposed bank of Allt Coire an t-Seilich from which the Geldie Lodge core was taken. Image is taken from the alluvial material located north west of the stream (Figure 3.12).

Figure 3.19 (right). Similar stratigraphy exposed 300m east on Geldie Burn. Two layers of stumps are visible. Geldie Lodge is in the background toward the southwest.

flat area, before the gradient along the Geldie Burn steepens and peat becomes more discontinuous. The peat stratigraphy at this deeper easterly section is shown in Figure 3.19.

To the west of Allt Coire an t-Seilich a series of dry ridges separated by peat troughs approximately 1m wide run at right angles from Geldie Lodge down-slope to the Geldie Burn. There are at least two large tree stumps buried in the peat sections.

National Vegetation Classes for the Geldie Lodge area are shown in Figure 3.20. Vegetation immediately around the river courses is *Nardus stricta-Galium saxatile* grassland (U5b), a calcifuge montane grassland. The wider blanket mire is classified as a mosaic community including *Calluna vulgaris-Vaccinium myrtillus* heath (H12), *Calluna vulgaris-Eriophorum vaginatum* blanket mire (M19) and E*rica tetralix-Sphagnum compactum* wet heath (M16). The distribution of these vegetation units is linked to local superficial deposits. Around the core site, M16 is the dominant unit, higher up the valley sides H12 becomes more important, with M19 important as an intermediary. This differentiation between riverside, valley bottom and valley side in the vicinity of Geldie Lodge is evident from a distance (Figure 3.16). Colour change from dark green to brown marks the transition from vegetation dominated by grass and sedge to that dominated by heaths and *Sphagnum*.

Geldie Lodge now lies well outside the area of woodland. The nearest extant trees are planted *Picea abies* just over 2km to the east (Figure 3.1 and 3.4), but it is clear trees have been present here in the past. In addition to the stumps emerging at the core site, large tree stumps can be seen emerging from the peat wherever rivers are eroding the peat (Figure 3.18 and 3.19). These are found both at the base of the peat and part way up the column. It is also clear that Geldie Lodge was by no means the

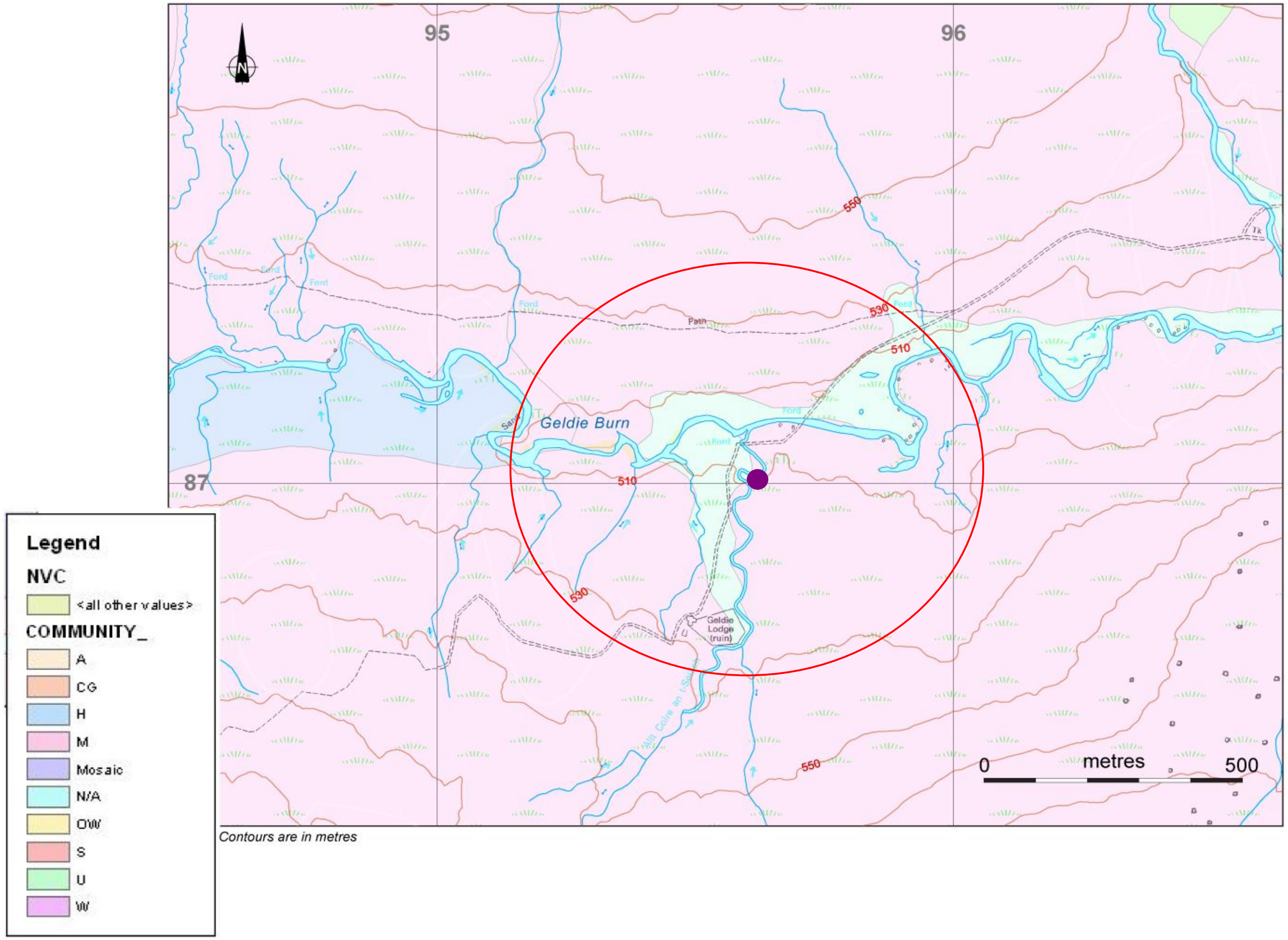


Figure 3.20 National vegetation classification near Geldie Lodge, core site (purple spot) courtesy of Scottish Natural Heritage. Key to Legend: A- aquatic, CG- calcicolous grassland, H- heath; M- mire; NA- not available, OW- open woodland, S- swamp and tall herb fen, U- calcifuge grassland and montane communities, W- woodland and scrub. Vegetation surveys are complete in the Geldie Lodge area. There are clear differences in vegetation on the alluvial fan of Allt Coire an t'Seilich and the Geldie Burn. The red line indicates the likely maximum RSAP for Geldie Lodge core site.

highest point for tree growth. There are tree stumps eroding from the peat to at least 600m, on the slopes above the headwaters of the Geldie Burn and the River Feshie.

The site was originally sampled as part of a study by Clark (2003, Figure 3.21). The peat face still retained evidence of her monolith-tin samples in September 2005 when cores were extracted using a 1.0m long, 5.0cm diameter Russian corer in two cores covering the full 139.0cm of the peat. Allowing for the extra 9.0cm of the nose cone of the Russian corer, the new stratigraphy is 19cm longer than Clark's. Basal sediments were sampled using a Livingston piston corer with a 60.0cm long, 5.0cm diameter chamber.

Unlike Doire Bhraghad and White Bridge, Geldie Lodge is not the best site in the area in terms of peat depth. Sampling of a thicker sequence 300m eastwards down the valley may have been preferable for temporal resolution and may have extended the record further back into the Holocene. However the opportunity to make a direct comparison between a pollen and a Coleopteran record compensates for the shorter sequence. The sediment stratigraphy in the stream face sampled also clearly demonstrates the presence of *Pinus*, stumps in the eroding river cliff and wood fragments in the core. There are no other problematic changes in stratigraphy. The Geldie Lodge assemblage is likely to include pollen recruited from a larger area than White Bridge or Doire Bhraghad, including the valley sides, though these are gentle and more distant from the core site. The Geldie Burn is unlikely to have influenced the development of the peat sequence, but Allt Coire an t'Seilich is currently undermining the base of the sequence and may have affected it in the past.

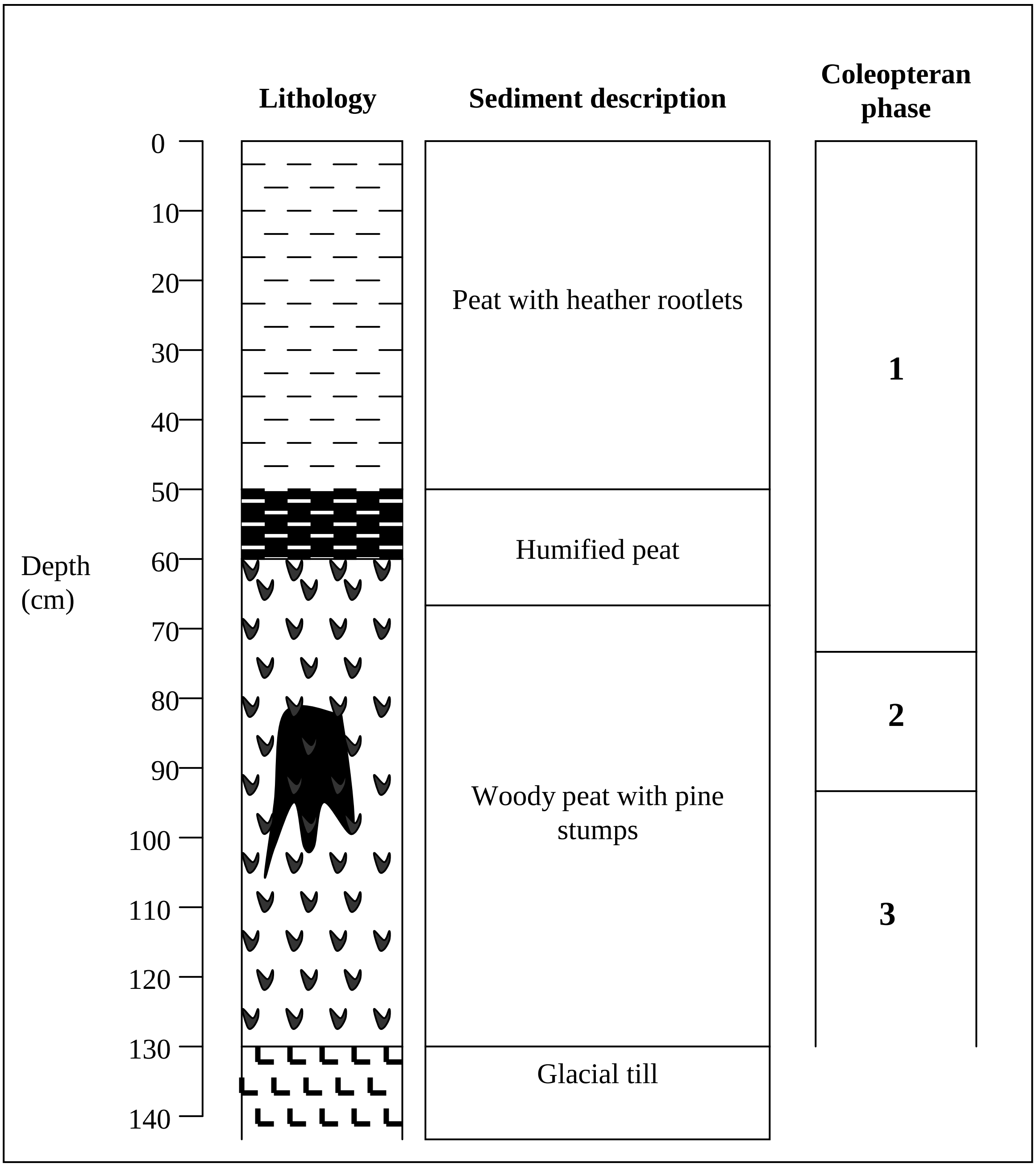


Figure 3.21 Coleopteran zones, sedimentary diagram and description of peat sampled from the bank of Allt Coire an t-Seilich, Geldie Lodge, Mar Lodge Estate, redrawn from Clark (2003).

3.4 Laboratory analyses

3.4.1 Storage of cores and pollen preparation

Cores were placed in 1.0m long, 5.0cm diameter semi-circular gutters, wrapped in polythene tubing, labelled, and sealed with duck tape. Cores were stored in the dark at 4°C until further analyses were carried out. The stratigraphies recorded in the field were enhanced by detailed sediment descriptions in the laboratory.

Cores were described prior to sub-sampling using the modified scheme of Troels-Smith (Aaby and Berglund 1986). Flat surfaces of the semi-circular cores were cleaned to aid observations; surfaces were scraped laterally to avoid contamination. Colour, compaction and texture of the sediment were noted, together with visible charcoal and wood fragments. Cores were sub-sampled using a razor and fine spatula that were cleaned and rinsed with distilled water between sub-samples. Samples of *c.* 1cm^3 were taken from sections no more than 2.0mm thick, to maximise temporal acuity. Initially cores were sub-sampled every 8cm, to establish areas of greatest interest. Once these sub-samples were counted, sections of greatest interest, for example rapid declines or increases in *Pinus* pollen values were sampled in greater detail. Sections of lesser interest, e.g. heath assemblages towards the top of a core, were not sub-sampled in such detail.

Sub-samples for pollen analysis were prepared for analysis in batches of eight by acetolysis (Moore *et al.* 1991). Treatment with 10% hot hydrofluoric acid was required only for a 15cm thick mineral band (100-115cm) at Doire Bhraghad and for basal sediment (106.5-114.5 cm) from the White Bridge core. All sub-samples were passed through 150μm metal sieves and retained on 10μm nylon sieves. *Lycopodium* spores were added to the sub-samples to enable concentration and influx counts to be calculated (Stockmarr 1977). *Lycopodium* may be present in the Mar Lodge area (Estate and NVC records, Stace 1991) but introduced spores were separable from sub-fossil ones by being degraded by double acetolysis treatment. Once processed, pollen residues were stored in silicone oil and sealed in clear plastic airtight vials at room temperature.

Slides were prepared using additional silicone oil to dilute the pollen residue and allow movement of individual grains where necessary. Cover slips were applied and sealed using clear nail varnish prior to counting. Counted slides were also stored, flat, in slide storage boxes.

3.4.2 Loss of mass on ignition, colorimetric analysis, particle size analysis

Loss of mass on ignition and colorimetric analysis of humic acids were carried out in combination. Extraction of humic acids follows Blackford and Chambers (1993), adapted by Robert McCulloch of the University of Stirling. Sub-samples of *c.* 5g were oven dried at 105°C for between 24 and 48 hours. After removal of 0.2g for colorimetric analysis, the remainder was ignited in a muffle furnace at 450°C for 8 hours. The ash was allowed to cool in desiccation jars, weighed and the percentage loss calculated.

Particle size analysis was carried out on only one section of the three cores, the 15cm thick mineral band at Doire Bhraghad at 2cm intervals. Particle size was determined by laser granilometry with a Beckman-Coulter Particle Size Analyser after light grinding with a rubber-ended pestle, sieving at 2.0mm and suspension in Calgon.

3.4.3 Radiocarbon dating

The depths of samples for radiocarbon assay were chosen in relation to changes in sediment and pollen stratigraphic data. With the exception of a 5.0cm slice (187.0-192.0cm) sampled at Doire Bhraghad (DB1) radiocarbon assays were made from 1.0cm slices of organic sediment. Sub-samples were cut using a razor blade and spatula, cleaned and rinsed between sub-samples in distilled water. Sub-samples were wrapped separately in aluminium foil, labelled and sealed in separate plastic bags, which were also labelled, and sent for radiocarbon assay immediately after sub-sampling to the Scottish Universities Environmental Research Centre ^{14}C Dating Laboratory at East Kilbride where sub-samples were chemically prepared. The humic acid fraction was dated in all cases by accelerator mass spectrometry (AMS). Dates are calibrated using OxCal 3.1 (Bronk Ramsey 2005) with atmospheric data from Reimer *et al.* (2004). Radiocarbon dates and calibrated ages are presented separately for each site in Chapters 4-6.

3.4.4 Pollen identification

Pollen analyses were made using a binocular Leica DM500 microscope. Counts were made at magnification x400 with critical examinations made at magnification x1000 under oil immersion. Pollen was identified by reference to Moore *et al.* (1991) and the University of Stirling pollen reference collection. Counts were based on a minimum of 500 grains total land pollen (TLP) except for one level, 74.5cm, from White Bridge, where the count was 452 grains. Pollen nomenclature follows Bennett (1984) and plant nomenclature follows Stace (1991).

Some pollen taxa, for example Cyperaceae and Poaceae, are identified only to family level. Separation of Poaceae to cereal type groups follows Andersen (1979).

Separation of *Corylus avellana* and *Myrica gale* remains controversial. Edwards' (1981) scepticism is questioned by the separation of these by Moore *et al.* (1991) and particularly by Blackmore *et al.* (2003) and, with due caution by Punt *et al.* (2003). Three categories were erected in this study: (a) *Corylus*, (b) *Myrica* and (c) *Corylus avellana* type to include grains not positively identified as either. Separation of tree birch from *Betula nana* (Prentice 1981) was not attempted.

The second area of taxonomic contention is the separation of the tetrad pollen of the Ericales group, including *Calluna vulgaris*, *Empetrum nigrum*, *Vaccinium* type, *Erica* spp, *Arctostaphylos*, *Pyrola* type and *Phyllodoce caerulea*. Pollen of this group was determined to species level if possible using the special key in Moore *et al.* (1991, p88) and following Foss and Doyle (1988). In this group, Ericaceae undifferentiated are grains not placed in any higher taxonomic level. Table 3.1 provides details of features used during routine counting to identify grains. Terms used describe the features searched for during counting. They are often qualitative and subjective but can differentiate grains.

Some possible plants included within a pollen taxon, e.g. *Erica ciliaris* and *Arctostaphylos alpinus* can be excluded as outside likely latitudinal range. More careful consideration is required in the case of *Empetrum nigrum* ssp *hermaphroditum* and *Phyllodoce caerulea*, whose altitudinal ranges are now above all three sites. The controls on altitudinal limits are likely to have been considerably different in the past. It is also possible that *Phyllodoce* grains could be misidentified as *Pyrola* type (exits 6a and 6b Moore *et al.* 1991, p88) or *Empetrum*. *Ledum palustre* is an introduced species from North America and *Corema album* is not listed as part of the British Flora (Stace 1991). *Pyrola* type includes *P. rotundifolia*, *P. media, P. minor* and *Moneses uniflora*.

Table 3.1 Identification and categorisation of pollen

Pollen taxa	Distinguishing features used during counting	Plant	Possible mis-identifications
Corylus avellana	Nexine and sexine continue right to the edge of the porus.	*Corylus avellana*: hazel	*Myrica gale*
Myrica gale	Endoaperture larger than ectoaperture	*Myrica gale*: bog myrtle	*Corylus avellana*
Corylus avellana type	Not identified positively as *Corylus* or *Myrica*	*Corylus avellana* or *Myrica gale*	
Arctostaphylos uva-ursi	Fairly large, globular tetrad with individual grains triangular obtuse, inner walls of tetrad slightly perforated	*Arctostaphylos uva-ursi*: bearberry	*Arctostaphylos alpinus*, inner walls more perforated, fewer endocracks
Calluna	Tetrad in a single plane; coarse scabrae-verrucae-gemmae; tetrad and colpi rather irregular	*Calluna vulgaris*: Ling Heather	Some *Pyrola* tetrads may be a single plane tetrad
Empetrum nigrum ssp *nigrum* type	Small triangular obtuse tetrad; darker appearance due to thick inner walls; psilate or granulate surface	*Empetrum nigrum* ssp *nigrum/hermaphroditum*: Crowberry. *Corema album*, Portuguese Crowberry	*Phyllodoce*; *Ledum palustre*
Erica tetralix	Mid sized globular to triangular obtuse tetrads, scabrate-verrucate surface, clear costae to the colpi	*Erica tetralix*: Crossed leaved heath. *E. ciliaris, E. umbellata*	Costae may be less obvious, possible confusion with *Vaccinium*
Erica cinerea	Large globular grain, colpi often widening toward equator, very distinct costae to colpi.	*Erica cinerea*: Bell heather	Some overlap with largest *Vaccinium* grains.
Vaccinium	Mid sized globular to triangular obtuse tetrads; surface psilate-scabrate-verrucate; costae to colpi insignificant or absent.	*Vaccinium* spp: bilberries	Some overlap with largest *E. cinerea* grains
Phyllodoce	Tetrad with short colpi with indistinct outline; surface psilate to scabrate-verrucate surface; detectable costae;	*Phyllodoce coerulea*: blue heath,	*Empetrum, Pyrola*
Pyrola type	Tetrad with short colpi with indistinct outline, surface psilate to scabrate-verrucate; costae detectable.	*Pyrola* sp: wintergreens. *Moneses uniflora*: one flowered wintergreen.	Fine ornament on *Calluna* may appear to be *Pyrola.*
Ericaceae undifferentiated	No positively identified features placing the grain firmly within other taxa.	Mainly *Calluna*, with obscured or hidden *Erica* spp, *Vaccinium* and *Empetrum*	

Pyrola type in Mar Lodge is most likely to include *Pyrola* spp, as *Moneses uniflora* is a lowland species found up to 300m only (Preston *et al.* 2002).

During counting pollen was assessed for deterioration and assigned into one of five categories: normal, crumpled or folded, split or torn, corroded, and degraded. Following Lowe (1981) and Tipping (1987), Indeterminate pollen was assigned to five categories: hidden, crumpled, split, corroded and degraded, indicating the reason for lack of identification.

Pinus stomata were counted as part of the routine count. Identification was made using pictures from Trautmann (1953) and Hansen (1995) and a dichotomous key from Sweeney (2004). In samples from the minerogenic band at Doire Bhraghad further stomata counts were made based on exotic counts only. Stomata in levels 114-100cm from Doire Bhraghad were counted to a pollen equivalent of 2500-4000 grains. Fungal and algal material was also counted, and in some cases identified (van Geel, 1978), providing information of bog surface conditions. Diatoms were counted and can be used to infer surface wetness of peat of sub-samples not treated with HF.

Microscopic charcoal was divided into five size classes (10-25µm, 25-50µm, 50-75µm, 75-100µm and >100µm) to provide evidence of vegetation burning (Cayless and Tipping 2002). In addition to these size classes, pieces of charcoal with a long axis of more than 150µm were encountered within the first pollen count, despite sieving at 150µm during pollen preparation. Systematic counting of large charcoal particles was not initially planned but these were subsequently noted. These largest microscopic fragments have been shown by Clark (1988), Clarke and Royall (1993) and Higuera *et al.* (2005) to be associated with fires within 100m of a site. Higuera *et al.* (2005) showed that not all local moderate to low severity fires were detected using charcoal larger than 125µm, but fewer false positives were found compared with macroscopic charcoal (larger than 500µm).

Pollen diagrams were drawn using *Tilia* software (Grimm 1993). All taxa are shown in percentage diagrams (Figures A.1a, A.2a, A.3a), but only principle contributing taxa are shown in concentration (Figures A.1b, A.2b, A.3c), and influx (Figures A.1c, A.2c, A.3c) diagrams.

4 Doire Bhraghad: results and interpretation

4.1 Introduction

The results and the interpretation of the results from the Doire Bhraghad core are presented here. Data including sediment descriptions and morphology, colorimetric data, percentage loss of mass on ignition (LOI) and radiocarbon assays are presented in Section 4.2. Descriptions of local pollen assemblage zones are presented in Section 4.3.1 and results of rarefaction analysis (palynological richness) are presented in Section 4.3.2. Dating models and pollen influx data are presented and described in Section 4.4. Interpretations of the Doire Bhraghad data form the final section of this chapter (Section 4.5). All pollen diagrams are presented in Appendix A.1.

4.2 Sediment description and morphology, colorimetric data, percentage loss of mass on ignition and radiocarbon assays

The sediment stratigraphy at Doire Bhraghad is shown in Table 4.1. Sediment from 192cm to 115cm consists of very dark brown amorphous peat. The light grey band of sediment between 115 and 100cm is most clearly seen in the field when unaltered by oxidisation; during initial field investigation it was referred to as an ‘inwash band’. The stratigraphic position of the minerogenic band within the mire and its particle size distribution are presented in Figure 4.1 and Figure 4.2. From 100 to 55cm sediment consists of dark brown to black peat with little identifiable plant material. Above 55cm the peat becomes lighter brown and contains more identifiable plant matter.

Investigation of the mire stratigraphy using an Eijkelkamp corer (Section 3.3) showed that the band is basin wide, and of near uniform thickness. Lower and upper boundaries between minerogenic and organic material are sharp. The upper surface of the band is up to 1.7m below the surface in the deepest sections of the mire and less than 50cm below the surface at the shallower edges of the mire (Figure 4.1). The gradient of the upper contact is lower on the east, north and southern sides of the basin than on the western edge. Particles are mainly in the size range from very fine silt to fine sand, but the particle size distribution is similar throughout its thickness (Figure 4.2). There is an increase of coarser particles between 111 and 107cm, particularly of fine gravel, but the percentage increase is less than 2%. Fine sand has the greatest variation, from 10% at the base of the band to 20% at 105cm. No other size category varies by more than 5%.

Table 4.1 Doire Bhraghad sediment description

Depth (cm)	Colour	Description	Troels-Smith classification
0-4	Light brown- dark yellow	Moss peat, including *Sphagnum*	Th4
4-32	Dark brown	Peat with identifiable plant material, including *Sphagnum*	Sh2 Th1 Dl1
32-55	Very dark brown	Peat with some identifiable plant material	Sh3 Th1 Dl+
55-100	Very dark brown-black	Very fine amorphous peat	Sh2 Th2
100-115	Grey, very thin dark brown streaks	a) Light grey clay and silt rich material with b) very thin dark brown organic bands	a. . Sh1 Th1 As2 Ag+ b Sh2 Th1 As1
115-140	Dark brown	Amorphous peat. Gradual change from previous unit. Wood fragments at 130cm.	Sh2 Th2
140-192	Dark brown	Amorphous peat, declining Dl content from base to surface	Sh2 Th1 Dl1

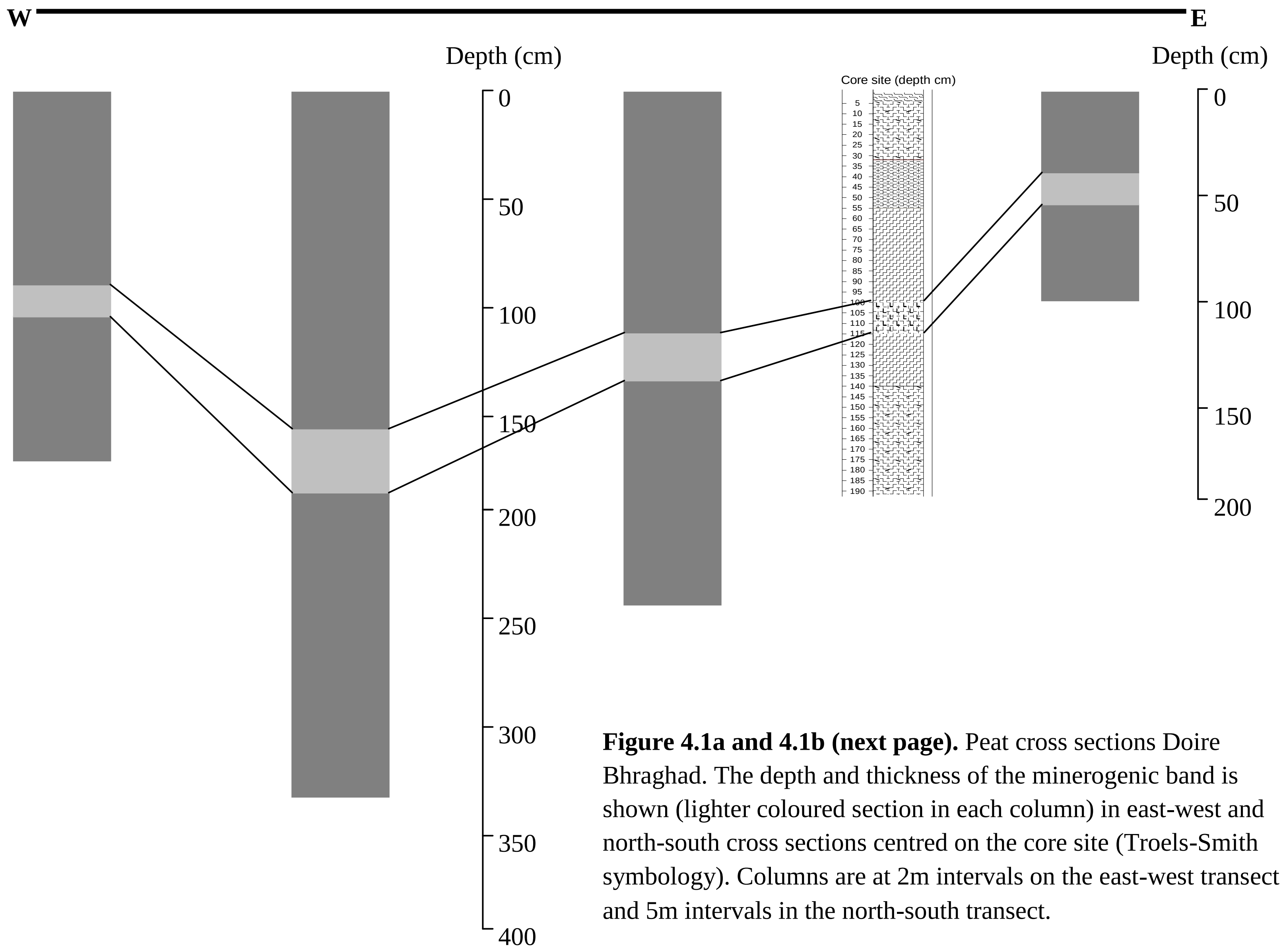
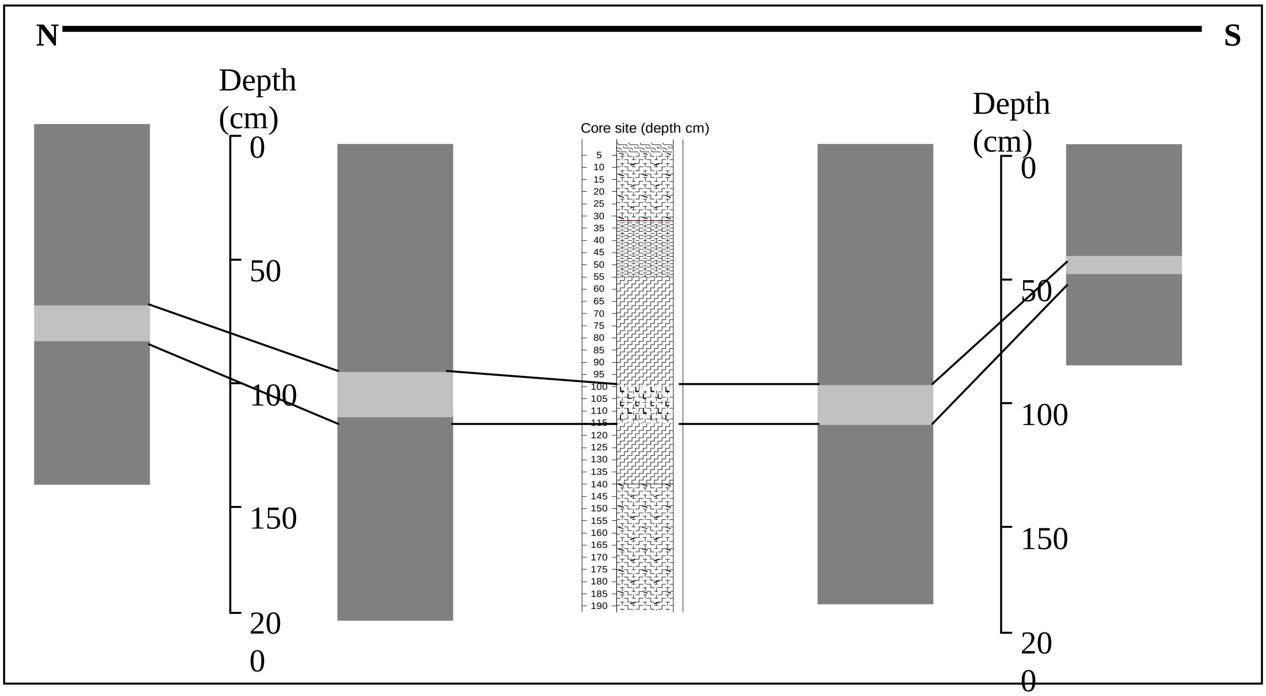


Figure 4.1a and 4.1b (next page). Peat cross sections Doire Bhraghad. The depth and thickness of the minerogenic band is shown (lighter coloured section in each column) in east-west and north-south cross sections centred on the core site (Troels-Smith symbology). Columns are at 2m intervals on the east-west transect and 5m intervals in the north-south transect.



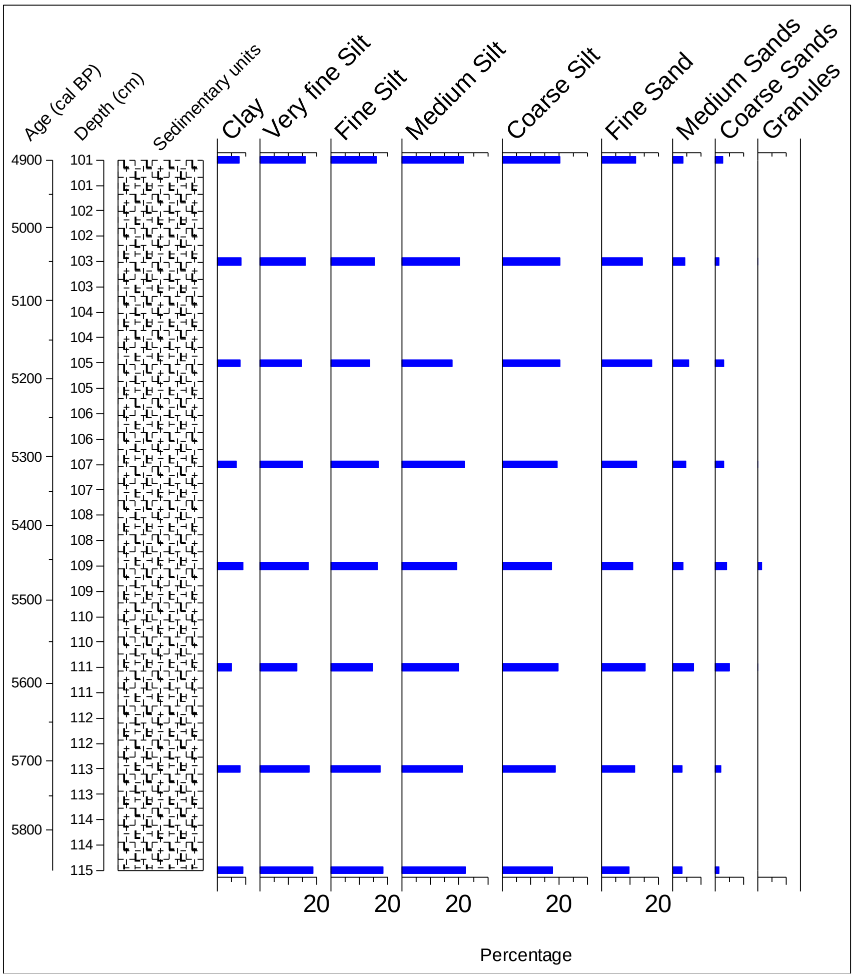


Figure 4.2 Particle size distribution of sediments in the minerogenic band

The deeper sections of peat revealed by the Eijkelkamp investigation are heavily dissected by tree roots, which made sampling difficult, but there were no further minerogenic sections identified below the base of the fully described core sequence.

Colorimetric light transmission data, measuring peat humification, and percentage LOI data, measuring carbon content, in this context organic carbon, are presented in Figure 4.3. Samples above 7cm lacked sufficient material to be analysed. Sediment below 150cm is highly organic (LOI greater than 80%); the lowest carbon content is from 110 to 102cm (less than 40%), but organic content falls below 80% between 80 and 150cm. In the uppermost 80cm LOI is in excess of 80%.

Colorimetric light transmission is the inverse of the LOI curve; transmission is highest (greater than 65%) from 110 to 102cm. Light transmission from 187 to 145cm varies from 40% by ±6% but shows no directional change. Above 145cm a rise to nearly 50% transmission is interrupted from 139 to 137cm by an abrupt drop to 35%, before returning to about 50%. From 135 to 119cm transmission steadily declines to less than 40%. Two abrupt increases in excess of 15% between 119 and 109cm (119-117 and 111-109cm) are separated by a very small decline. From high transmission values (over 60%) at 100cm, the subsequent decline is to the lowest values for the sequence, 20% ±4% between 55 and 35cm. An increase in transmission to 25-35%, between 33 and 11cm, precedes the rise to around 50% in the uppermost levels.

There are three radiocarbon assays for Doire Bhraghad (Table 4.2). There may be an *Ulmus* decline in the pollen stratigraphy (Figure A.1a) at 107-105cm, but it is too weakly expressed to be reliable.

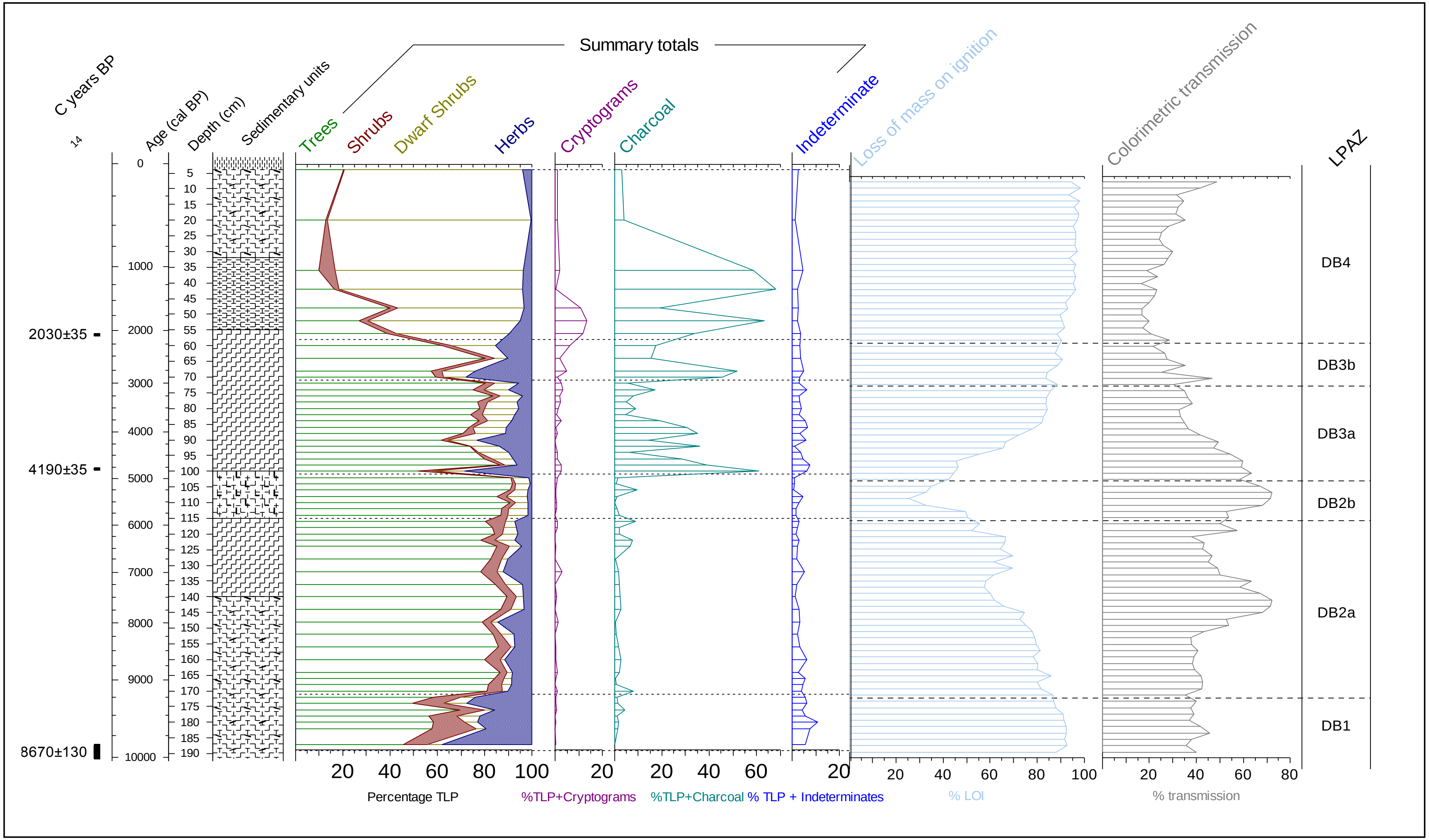


Figure 4.3 Doire Bhraghad percentage loss of mass on ignition and percentage colorimetric transmission, with summary percentage pollen diagrams

Table 4.2 Results of radiocarbon assays for Doire Bhraghad

			Radiocarbon age	Loss of mass on ignition	$\delta^{13}C_{PDB}$	Calibrated age ±2σ using OxCal 3.1	
Laboratory code	Sample code	Depth (cm)	years BP ±1σ	% LOI	‰ ±0.1	Range, cal years BP	Midpoint cal BP
GU-20333	DB3	56-57	2030±35	90	-28.0 (assumed)	2160-1940	2050
GU-17256	DB2	99-100	4190±35	42- 47	-28.6	4890-4660	4775
GU-10792	DB1	187-192	8670±130	88 (186-187cm)	-31.1	10250-9450	9850

4.3 Descriptions of pollen assemblage zones and rarefaction analysis

4.3.1 Description of pollen assemblage zones

The Doire Bhraghad sequence is divided into four local pollen assemblage zones (lpaz), DB1-4, two of which are sub-divided (DB2a, b and DB3a, b), marking major and minor changes in the pollen stratigraphy interpreted from stratified cluster analysis implemented via CONISS (Grimm 1987). Descriptions of lpaz are presented below. Diagrams showing percentage and concentration data (Figures A.1a and b) are presented in Appendix A.

lpaz DB1, 171-187cm, *Betula-Pinus sylvestris*-Cyperaceae-Poaceae

Radiocarbon assay, 187-192cm, 8642±130 years BP

Betula dominates the assemblage. The *Pinus* percentage increases gradually and stomata are present from midway through the zone. Poaceae and Cyperaceae have relatively high pollen percentages, along with *Corylus* and *Salix*.

Betula percentages are consistently around 40-50% TLP. The *Pinus* percentage increases above 10% TLP at 180cm and a peak of 25-30% TLP at 178cm coincides with the first appearance of pine stomata. The pollen concentration curves of *Betula* and *Pinus* are similar to their percentage curves. *Quercus* and *Ulmus* are continuously present at less than 1% TLP but *Alnus* is only sporadically present.

Salix and *Corylus* pollen accounts for about 5-10% TLP each, both have their peaks early in the zone, with declines after 182cm. Dwarf shrubs comprise about 5-10% TLP with only *Calluna* and *Myrica* consistently present. *Calluna* percentage does not increase above 2% TLP, while *Myrica* fluctuates between 1% and 5% TLP.

Cyperaceae has a single level peak of just under 35% TLP at the very base of the zone, its highest percentage of the sequence, following this early peak the curve fluctuates around 10% TLP. Poaceae is also important with percentages fluctuating between 5 and 10% TLP throughout the zone. The only other herb taxa with a consistent presence in DB1 is *Filipendula* with percentages of 1-2% TLP. *Myriophyllum alterniflorum* is present at 172, 174 and 189cm.

There are very few Cryptograms in DB1 and Charcoal also has very low percentages. Fungal material is common throughout this zone at percentages of less than 10% TLP plus Unknowns, but there are no particular specific types or ecological indicators consistently present. Diatoms are present throughout the lowest assemblage zone. Algal material identified in levels 172, 174, 176 and 178 were van Geels' (1978) type 58, an Algal type identified as indicative of open water (van Geel 1978).

lpaz DB2a, 115-171cm, *Pinus sylvestris*-*Betula*-Cyperaceae-Poaceae

Pinus percentage continues to increase from the top of DB1, dominating the assemblage for all of DB2a. *Betula* falls but remains a minor presence. Poaceae and *Calluna* percentages decline slightly compared to DB1.

Pinus pollen percentages reaches 60-75% TLP and concentrations also increase consistently throughout the zone. Pine stomata have an almost continual presence throughout this zone; they are absent from levels 118 and 144 but show the highest percentages for the whole sequence. The *Betula* percentage falls from 15-20%

TLP at the base to a consistent 10-15% TLP in the middle and upper levels of the zone. *Alnus'* first appearance is in DB1, but *Alnus* is present continuously from 148cm; the *Alnus* percentage does not increase above 1% TLP in DB2a. *Quercus* is present in every level except 164cm, typically at about 1% TLP, but with a slightly higher percentage through the middle of the zone, around 2-3% TLP. *Ulmus* is less consistently present, at similar percentages to DB1. *Salix* shows a decreased percentage compared to DB1 and in contrast to DB1 there are three levels in which it is absent (120, 134 and 164cm).

Calluna is present throughout the zone but at consistently low percentages of around 1-2% TLP; Ericaceae undifferentiated also has low percentages. *Empetrum* is only sporadically present in DB2a with percentages of up to 1% TLP. *Vaccinium* is largely absent between 128 and 166 and where present shows reduced percentages compared to DB1.

The contribution to the pollen sum from both the Cyperaceae and Poaceae curves declines in DB2 compared to DB1, down to around 5% and 1-3% respectively. Apiaceae is present in 5 of the lowest 7 levels (absent from 156 and 168) but appears only once more (120cm). There are two levels with an Asteraceae presence (124 and 170cm).

Charcoal has a minor peak in all classes above 124cm, but is otherwise unimportant. Diatoms have a stronger presence compared to DB1, with about 5% TLP plus Unknowns at the base (160-170cm) and the top (115-130cm). There is a consistent low level presence of Algal material throughout the zone, again particularly of van Geels' (1978) type 58, indicating open water.

lpaz DB2b, 101-115cm, *Pinus sylvestris*

Pinus pollen dominates the assemblage with more than 75% TLP in every level, but there are almost no pine stomata. Other taxa are relatively unimportant.

With percentages between 75% and 90% TLP this zone represents the peak presence for *Pinus* pollen in this sequence. *Pinus* concentration is also highest in this zone, but pine stomata are present only at 114cm. *Betula* declines from 5% TLP at the base to about 1% at the top of the zone and other arboreal pollen taxa are at 1% TLP or less.

Calluna and *Vaccinium* are consistently present at about 3-5% and less than 1% TLP respectively but *Empetrum* is absent from 106 and 102cm with percentages of 1-2% TLP elsewhere. Other Dwarf Shrubs are less important.

Poaceae is low (1-2% TLP), the lowest percentage for Poaceae for the column, and shows no directional change. Cyperaceae is absent from two levels (110 and 104cm) and is at less than 1% in the other levels. *Filipendula* is less consistently present than in previous zones and shows lower percentages, less than 1% TLP, in the four levels in which it is present (100, 104, 110 and 114cm).

Sphagnum starts to be more consistently present in DB2b. Although levels 104, 106 and 108 have only one or two grains, *Sphagnum* is only absent from one level (114cm). Charcoal percentages are generally low but there is a minor peak in all class sizes at 106cm.

lpaz DB3a, 71-101cm, *Pinus sylvestris*-Poaceae-*Calluna vulgaris*-*Quercus*

Radiocarbon assay, 99-100cm, 4190±30 years BP

Pinus percentage is high but concentration declines and stays low for the rest of the column. Poaceae, *Calluna* and *Quercus* are present throughout the zone with similar percentages. The base of this zone marks the start of large Charcoal percentages.

Pinus pollen has lows of below 50% and around 60% TLP at 72 and 90cm, returning to about 70-80% TLP after each trough, before declining to 60% TLP at the top of the zone. Concentration falls at the base of the zone and remains low to the top of the sequence. Pine stomata are absent only from 90 and 94 cm. *Betula* recovers slightly from DB2b, from 3% to just under 10% TLP. *Quercus* is present throughout the zone and increases up to about 10% TLP at 84cm. *Alnus* increases consistently but never exceeds 5% but *Ulmus* is absent from four levels (80, 88, 92 and 94cm), where present it is typically less than 1% TLP. *Populus* and *Sorbus* are present in three levels each: 78, 88, 94cm and 78, 84, 92cm respectively.

The percentage of *Calluna* pollen shows a minor peak in the levels that *Pinus* declines; this is not reflected in the concentration curve and for the zone as a whole *Calluna* shows no directional change, fluctuating between 5 and 10% TLP. Ericaceae undifferentiated is largely unchanged with percentages of about 2% TLP and absences at 76, 84, 90, 98 and 100cm. Other Dwarf Shrubs are also relatively unimportant.

Poaceae pollen has two major peaks (15-20% TLP) at 100cm and from 90-92cm; although less important in other levels the percentage never drops below 3% and is usually more than 5% TLP. *Potentilla* type is present in all but 4 levels (78, 80, 86 and 94cm) but is never more than 1% TLP. *Filipendula* is present in 4 levels (74, 84, 88 and 92cm) but the percentage is never higher than 1% TLP. *P. lanceolata* has its first appearance in this zone and has a presence in 5 levels (76, 82, 84, 86 and 90cm) but there are never more than 2 grains in any level.

There are two levels with *Tilletia* spores (74 and 76cm), but *Sphagnum* is unimportant with percentages of less than 2% TLP plus Cryptograms. *Pteridium aquilinum* is occasionally present.

The base of this zone marks the start of large Charcoal counts and the ratio of large to small fragments changes. An initial peak at the base of the zone is heavily weighted towards particles of less than 50μm, but these categories decline more rapidly than particles of greater than 50μm. There is a second peak for all classes midway through the zone. Fungal and Algal material is present consistently throughout the zone. Algal types linked by van Geel (1978) with open water, type 60 and type 58 (96cm), type 58 (72cm) and type 108 (84cm) are identified in this zone.

lpaz DB3b, 54-71cm, *Pinus sylvestris*-Poaceae-*Calluna vulgaris*-*Sphagnum*

Radiocarbon assay, 56-57cm, 2030±30 years BP

Pinus pollen is still the most important taxa and pine stomata are present in each level. *Betula* increases slightly and Poaceae is also important. Charcoal is very high in the first two levels of the zone, but decreases slightly in the second two. *Calluna* is less important than in DB3a.

Pinus is always higher than 50% TLP, with a peak of 65% TLP at 64cm; pine stomata are present in every level. *Betula* increases slightly from 5% (68cm) to 10% (64cm) but *Alnus* and *Quercus* show low percentages (1-2%) and no directional change. *Ulmus* continues the decreased presence of DB3a with two levels with no presence and very low percentages (less than 1%) in the other two. *Salix* is absent in just one level (68cm) but presence in the other levels is registered by single grains.

Calluna is around 10-15% TLP in three out of four levels but has a single level dip (64cm) to less than 1% TLP, interrupting its upward trend from the base of

DB3a. Other Dwarf Shrubs are relatively unimportant.

Poaceae is still important, in excess of 15% in 3 out of 4 levels and a peak, at 70cm, of 20% TLP. Cyperaceae is also present in all levels but at percentages more typical for the column, 1-2% TLP. *Filipendula* is present in two levels (60 and 68cm) at less than 1% TLP. *P. lanceolata* has two levels with a presence (64 and 68cm) with a single grain in each level, in level 64 there is also a single grain of *Plantago* undifferentiated. *Potentilla* type pollen is present in 3 out of 4 levels at percentages similar to other zones.

Sphagnum is present in all four levels at between 2 and 4% TLP plus Cryptograms and *Pteridium aquilinum* is absent from the lowest level but present in the upper three at around 1% TLP plus Cryptograms.

Charcoal is important throughout the zone and has a large peak at the base of the zone, particularly for particle sizes of less than 50µm. Diatoms decline steadily from just 4% TLP plus Unknowns at the base of the zone down to zero at the top of the zone. There are no diatoms in the last zone (DB4). Algal material is absent from level 68cm, the only presence of algal material with an identifiable ecological indicator is in level 64cm, where type 58, indicative of open water is identified (van Geel 1978).

lpaz DB4, 4-54cm, *Calluna vulgaris-Sphagnum-Vaccinium-Empetrum*

All arboreal pollen taxa decline. *Calluna* is dominant with other Dwarf Shrubs also important. *Sphagnum* and Charcoal smaller than 50µm are important at the base of the zone.

Pinus comprises 35% TLP at the base of the zone. It decreases to between 5 and 10% TLP in the middle of the zone before increasing to between 15 and 20% TLP above 36cm. Stomata are present only in the uppermost two levels. *Betula* comprises 5% TLP at the base of the zone and decline to 1-2% TLP. Other arboreal pollen taxa are unimportant.

Calluna increases from just 15% TLP at the base of the zone to just over 70% TLP at 20cm. There are slight increases in the percentages of Ericaceae undifferentiated and *Empetrum* and *Vaccinium* show column high curves in this zone. *Empetrum* is absent from 36cm, but elsewhere fluctuates at around 5% TLP. The *Vaccinium* percentage reaches around 10% TLP (56cm and 4cm) and *E. cinerea* and *tetralix* are occasionally present.

Cyperaceae and Poaceae are relatively unimportant in the final zone. Poaceae is present in every level, although with only a single grain at 20cm, but it’s percentage drops from 5% at the base of the zone to about 1% TLP at the top. Cyperaceae is absent from 48cm and declines to less than 1% TLP above 20cm. *Filipendula* is present less often than in previous zones and is absent from 36, 48 and 52cm; *Potentilla* type is present in just three levels (44, 48 and 52cm), less consistently than in previous zones. *P. lanceolata* is present in just two levels (4 and 44cm).

At the base of the zone a *Sphagnum* peak of over 10% TLP plus Cryptograms covers 3 levels (48, 52 and 56cm), these are the highest *Sphagnum* percentages in the column. *Sphagnum* declines in importance abruptly over the last four levels. *Pteridium aquilinum* is present only in the first and last levels and *Sellaginella sellaginoides* is present at the base of the zone (52 and 56cm).

There are high Charcoal percentages throughout the zone, particularly of particles less than 50µm (around 60% TLP plus Charcoal); Charcoal almost disappears above 36cm. Diatoms are entirely absent from the zone but Fungal material is present in every level, including a peak of nearly 20% TLP plus Unknowns

(44cm), this is coincident with a very large peak (40% TLP plus Unknowns) of Algal material including type 58 of van Geel (1978). Algal remains disappear above 44cm.

4.3.2 Description of results from rarefaction analysis

Results from rarefaction analysis are shown in Figure 4.4. Values range from 37.3 (174cm) to 19.4 (104cm). There are periods of directional change, in lpaz DB1, DB2a, DB3b and DB6 but lpaz DB2b and DB3a are more variable. Palynological richness trends up erratically in DB1. The lowest value is at 182cm (23.8) and the highest (37.3) is at 174cm. A brief decline in values to 27.8 (168cm) is followed by a more sustained decline to 21.4 (148cm). A small rise and fall (148-140cm) is followed by another sustained rise in values (22.6-27.8) from 136 to 118cm. Between 118 and 70cm, palynological richness is erratic. Values between 104 and 92cm increase and decrease again rapidly, elsewhere directional change is limited to three levels or less. A small rise between 70 and 60cm (28.6-31.5) precedes a final steady decline to 20.2 at 20cm.

4.4 Dating model and description of pollen influx

4.4.1 Dating model

Sediment becomes less consolidated towards the surface and sediment accumulation rates reflect this, becoming more rapid towards the surface (Table 4.5). During initial investigation it was assumed that the minerogenic bands represented inwashed material and that they were likely to be deposited more rapidly than the rest of the sequence. Assay DB2 was placed above the inwash bands to avoid sampling possibly reworked organic matter. There is no evidence to suggest very rapid accumulation of the minerogenic bands (Table 4.2 and 4.3, Figure 4.5), furthermore

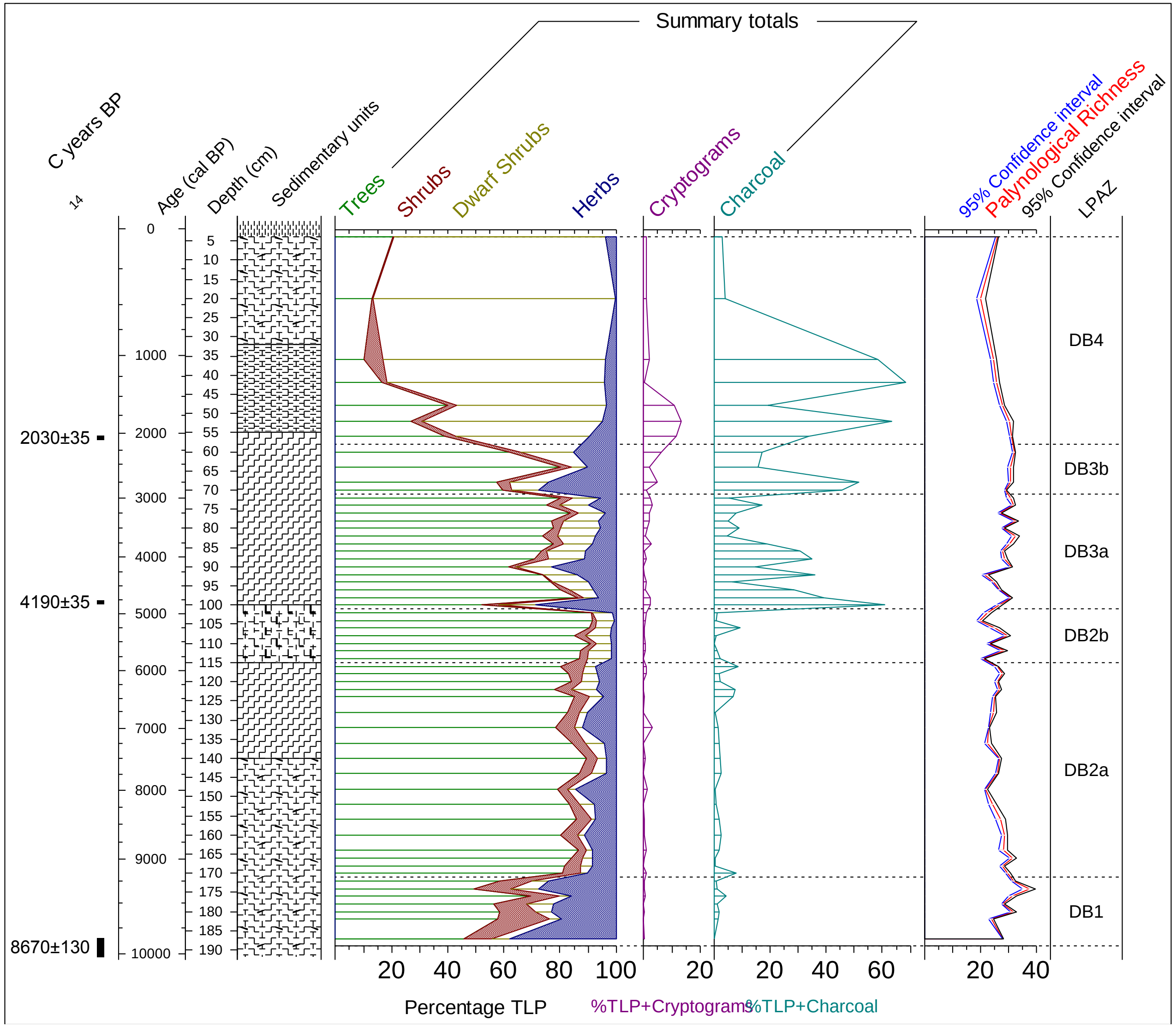


Figure 4.4 Results of Doire Bhraghad rarefaction analysis, with summary percentage pollen diagrams.

LOI shows that the reduction in organic content begins below the visibly obvious minerogenic section and continues to be depleted above it.

It is likely that the origin of the mineral material in the mire sequence is allochthonous, perhaps from the basin slopes, but there is no evidence from the radiocarbon assays available to indicate either an increased accumulation rate or a truncation of the sequence.

Table 4.3 Doire Bhraghad radiocarbon dates and calculated accumulation rates

			Sedimentation rates calculated from surface		Sedimentation calculated from date above	
Stratigraphic position	Date range ±2σ (cal years BP)	Midpoint (cal years BP)	Range of sedimentation rates	Mean rate of sedimentation	Range of sedimentation rates	Midpoint to midpoint
56-57cm	2160-1940	2050	34.0-37.9 cal yr cm^{-1}	35.9 cal yr cm^{-1}	34.0-37.9 cal yr cm^{-1}	35.9 cal yr cm^{-1}
99-100cm	4890-4660	4775	46.6-48.9 cal yr cm-1	47.5 cal yr cm^{-}	58.1-68.6 cal yr cm^{-1}	63.4 cal yr cm^{-1}
187-192cm	10250-9450	9850	49.2-53.4 cal yr cm^{-1}	51.3 cal yr cm^{-1}	49.6-60.7 cal yr cm^{-1}	55.2 cal yr cm^{-1}

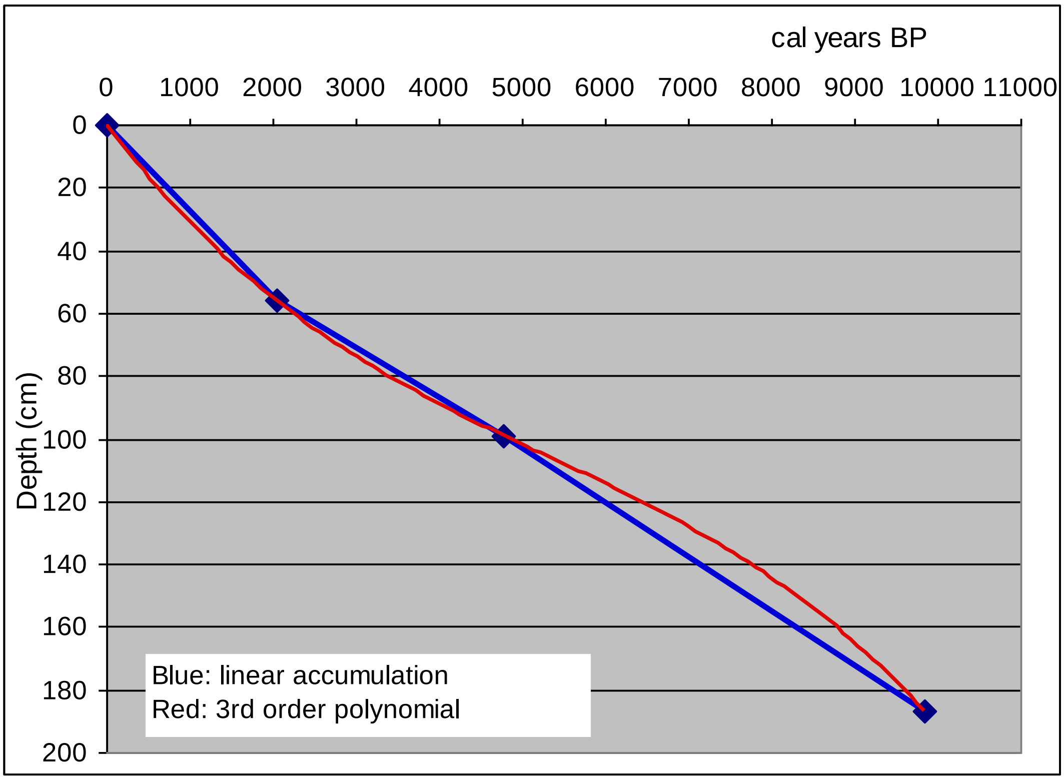


Figure 4.5 Doire Bhraghad, age-depth model

The simplest dating model is linear accumulation, but a linear solution gives sudden changes in accumulation that do not reflect real accumulation (Bennett 2003). As one of the functions of the dating model is to provide pollen influx data, it is better to use a polynomial solution (Figure 4.5); a third polynomial curve is used to calculate pollen influx for Doire Bhraghad. Assemblage zones generated from percentage pollen data are retained for pollen influx; descriptions of pollen influx are given below (Section 4.4.2). Influx diagrams for selected taxa from Doire Bhraghad are presented in Figure A.1c.

4.4.2 Descriptions of pollen influx data

lpaz DB1, 171-187cm, *Betula-Pinus sylvestris*-Cyperaceae-Poaceae

***c*. 9200-9850 cal BP**

Betula pollen influx is initially 750-1000 grains cm^{-2} yr^{-1} but declines to around 500-600 grains cm^{-2} year^{-1} at the top of the zone. *Pinus* is typically less than 500 grains cm^{-2} yr^{-1} except for a single level peak of 1000 grains cm^{-2} yr^{-1} at *c*. 9500 cal BP. *Calluna* pollen accumulates at rates of up to 100 grains cm^{-2} yr^{-1} in DB1, but other arboreal and shrub taxa accumulate at less than 50 grains cm^{-2} yr^{-1}. Poaceae accumulates at around 100 grains cm^{-2} y^{-1} throughout the zone and Cyperaceae exceeds 200 grains cm^{-2} yr^{-1} for the whole zone, with a peak at the very base of 700 grains cm^{-2} yr^{-1}.

lpaz DB2a, 115-171cm, *Pinus sylvestris*-Pine stomata-*Betula*-Cyperaceae-Poaceae

***c*. 5850-9200 cal BP**

Accumulation of *Pinus* pollen exceeds 1000 grains cm^{-2} yr^{-1} at the base of the zone. This increases to between 1000 and 2000 grains cm^{-2} yr^{-1} from *c*. 6200-8960 cal

BP and exceeds 2500 grains cm^{-2} yr^{-1} after *c*. 6200 cal BP. *Betula* accumulation declines consistently from the base of the zone (around 400 grains cm^{-2} y^{-1}) to about 250 grains cm^{-2} yr^{-1} at *c*. 6200 cal BP but recovers to around 500 grains cm^{-2} yr^{-1} after this. *Quercus* accumulation exceeds 100 grains cm^{-2} yr^{-1} at c. 7000 cal BP and *Alnus* accumulates at about 100 grains cm^{-2} yr^{-1} at c. 5900 cal BP, but *Ulmus* values remain low throughout. *Calluna*, *Empetrum* and *Vaccinium* accumulation rates increase slightly after *c*. 6200 cal BP, but remain at low values. Cyperaceae values are consistently at 100 grains cm^{-2} yr^{-1} except between *c*. 7050-7750 cal BP, where influx falls below 50 grains cm^{-2} yr^{-1}. Poaceae is also relatively unimportant, accumulating at between 50 and 100 grains cm^{-2} yr^{-1} for the whole zone.

lpaz DB2b, 101-115cm, *Pinus sylvestris*

c. 4910-5850 cal BP

Total accumulation rates are very high in DB2b, with peaks of over 3500 grains cm^{-2} yr $^{-1}$. *Pinus* exceeds 3000 grains cm^{-2} yr $^{-1}$, except from *c*. 5300-5520 cal BP where it drops to 2000 grains cm^{-2} yr^{-1}. *Betula* declines from around 400 to less than 200 grains cm^{-2} yr^{-1}, *Calluna* increases slightly to about 300 grains cm^{-2} yr^{-1} but other taxa are relatively unimportant.

lpaz DB3a, 71-101cm, *Pinus sylvestris*-Poaceae-*Quercus*

c. 2940-4910 cal BP

This zone has some of the lowest total accumulation rates of the sequence. Before *c*. 4200 cal BP, total influx is just over 1000 grains cm^{-2} yr^{-1} but influx declines to less than 500 grains cm^{-2} yr^{-1} after this. At the base of the zone *Pinus* accumulation rate is around 1000 grains cm^{-2} yr^{-1}. It remains around this value until *c*. 4040 cal BP, when values fall again to less than 500 grains cm^{-2} yr^{-1}. *Betula* and other arboreal taxa are unimportant and *Calluna* accumulation has fallen, but Poaceae influx has two large peaks at *c*. 4710 (500 grains cm^{-2} yr^{-1}) and from *c*. 4040-4200 cal BP (250 grains cm^{-2} yr^{-1}).

lpaz DB3b, 58-71cm, *Pinus sylvestris*-Poaceae-*Calluna vulgaris*-*Sphagnum*

c. 2170-2940 cal BP

The total accumulation remains low (less than 1000 grains cm^{-2} year^{-1}), but has increased slightly from the top of DB3a. Accumulation decreases from around 700 grains cm^{-2} yr^{-1} at the base of the zone to around 500 grains cm^{-2} yr^{-1} at the top of the zone. *Pinus* remains at similar values to DB3a. Poaceae has a large peak (300 grains cm^{-2} yr^{-1}) in the lower half of the zone (*c*. 2630-2940 cal BP). Other taxa remain unimportant.

lpaz DB4, 4-58cm, *Calluna vulgaris*-*Sphagnum*-*Vaccinium*-*Empetrum*

c. 50-2170 cal BP

Pinus increases slightly at the base of the zone (1500 grains cm^{-2} yr^{-1}) but declines between *c*. 1400 and 340 cal BP, before recovering to about 1000 grains cm^{-2} yr^{-1} after that. No other arboreal taxa are important in this zone.

Calluna increases from 1000 grains cm^{-2} yr^{-1}) at the base of the zone to a peak of over 4000 grains cm^{-2} yr^{-1} at the top of the zone. Accumulation rates of *Empetrum* and *Vaccinium* are relatively high, typically above 100 grains cm^{-2} yr^{-1}. *Myrica* has two large peaks of 500 and 1200 gains cm^{-2} yr^{-1} at *c*. 1820 cal BP and 1045 cal BP. Poaceae has two smaller peaks of between 100 and 200 grains cm^{-2} yr^{-1} at *c*. 1045 and

2050 cal BP. *Sphagnum* has accumulation rates of up to 600 grains cm^{-2} yr^{-1} below *c*. 1620 cal BP, but values of less than 100 gains cm^{-2} yr^{-1} after that.

4.5 Interpretation of data from Doire Bhraghad

lpaz DB1, 171-187cm, *c.* 9200-9850 cal BP

Betula-Pinus sylvestris-Cyperaceae-Poaceae

Basin environment

At present the surface dries out between about June and September but has standing water a few centimetres deep for the remainder of the year. The presence of aquatic or sub aquatic plants such as *Myriophyllum alterniflorum* and *Callitriche*, suggests that initially the basin was wetter than now. In several visits made to the site over the period 2002-2009, at all times of the year, no aquatic plants have been seen growing in the basin. There are several appearances of algal remains associated with open water by van Geel (1978) between *c*. 9240 and 9500 cal BP.

The Doire Bhraghad kettle hole’s modern form, open at the southern end (Section 3.2), means it is unclear whether the southern edge of the basin is a solid barrier, forming a pond with a surface outlet, or is permeable, retaining sediment but allowing through-flow of water. The basin has never received stream or river input as the open southern end of the basin slopes away to the south. It is possible that the site dried out during DB2b (see below), however even if Doire Bhraghad retained surface water throughout the Holocene it remained small enough to be regarded as a small hollow in terms of pollen source area (Calcote 1995, 1998). Permanent surface water would maintain the mire surface as an opening within the canopy, preventing trees from closing the gap in the canopy.

Cyperaceae make up nearly 40% TLP at the base of the zone and at least 10% TLP for the rest of the zone. Huntley and Birks (1983) found sporadic values of up to 50% TLP were indicative of sedge swamp, and Bunting (2003) showed Cyperaceae to have an RSAP of 2m or less. Initially Cyperaceae was dominant within the basin, and remained very important on the mire surface. High LOI percentages within this zone probably derive from Cyperaceae with aquatic plants and algal remains also common in the pond.

Fire

There is no evidence to suggest fire affecting the local area during this zone. There are no levels with large quantities of microscopic particles or levels with particles with an axis longer than 150μm within this zone.

Vegetation

In Glen Affric, Shaw (2006) found a regression intercept of 13.5% within a 20m source area. With percentages of up to 50%, *Betula* was locally present; influx suggests a semi open to closed canopy (Jensen *et al.* 2006, Hattestrand *et al.* 2008). *Pinus* was probably present locally initially; it was definitely present by *c.* 9588 cal BP when stomata are first recorded. The probable semi open canopy suggests *Betula* and *Pinus* were attempting to occupy the same locations, a competitive relationship. *Pinus* pollen percentages increase, becoming briefly dominant at *c.* 9500 cal BP, principally at the expense of pollen of *Corylus* and Poaceae, probably as a result of these taxa's inability to compete with year-round increased canopy density. In addition to this, modern conditions in the Mar Lodge area are marked by a high incidence of frost days into late May (McClatchey 1996), conditions likely to interfere with the flowering of *Corylus*, typically between January and March (Stace 1991). Seasonality may have been more marked from *c.* 8950 to 3950 cal BP (Anderson *et al.* 1998, Allen *et al.* 2007) and similar before and after these dates (Allen *et al.* 2007), suggesting an unusual competitive advantage for *Pinus* in a woodland situation (Section 2.2).

In contrast the continued abundance of *Betula*, according to percentage, concentration and influx suggests a strong, probably competitive presence. This is exemplified by the oscillations in dominance between *Pinus* and *Betula* after *c.* 9500 cal BP. These changes are not associated with increased charcoal, therefore the establishment of *Pinus* in the landscape does not appear to have been encouraged by increased fire in the landscape.

The high percentage of arboreal pollen suggests *Betula* to be forming a dense canopy. Influx data are in better agreement with a lighter canopy. The initial influx of *Betula* at Doire Bhraghad, about 1000 grains cm^{-2} year^{-1} exceeds Jensen *et al.*'s (2007) finding for *Betula* sub-alpine woodland (240-720 grains cm^{-2} year^{-1}) and is in agreement with Hattestrand *et al.*'s (2008) estimate for birch woodland (500-1200 grains cm^{-2} yr^{-1}) but considerably lower than their value of over 7000 grains cm^{-2} year^{-1} for mid-Boreal birch forest. In DB1 influx values do not reach values found by these authors to indicate dense *Pinus* woodland.

Corylus was probably a part of this relatively dense *Betula* canopy. Birks (1989, page 508) suggests that occasional low values (1-5%) of *Corylus* at Devensian late-glacial sites 'cannot be attributed to definite local presence'. With *Corylus* consistently around these percentages at Doire Bhraghad, within a probably closed canopy, local presence of *Corylus* is likely. Local presence of *Corylus* is in agreement with gaps within the *Betula* canopy, allowing flowering of *Corylus* (Mitchell 2005). *Salix* also has high enough percentages to be locally present (Huntley and Birks 1983). A semi open or closed canopy restricts the input of long distance input to the pollen assemblage, as decreased between-trunk space reduces wind speed (Tauber 1964, Sugita *et al.* 1999, Bunting *et al.* 2004, Sugita 2007) allowing airborne pollen to come to rest (Section 2.3).

The character of the surrounding land suggests separate locations for *Corylus* and *Salix*. *Salix* could have been growing within the basin itself but also on the area of sloping land adjoining the basin to the south. This area is very wet today, with low flows and ponded water from the kettle hole and the hillside. The substrate consists of peat just 10 to 15cm thick which could only have accumulated extremely slowly, giving a similar substrate throughout the Holocene (Section 3.4).

Declines in *Corylus* pollen indicate that *Pinus* replaced *Corylus* in the local woodland. It seems likely that *Pinus* initially occupied the same gaps in the canopy that *Corylus* exploited. Despite the typically poor competitive performance of *Pinus* in a woodland context, the acidic base poor soil conditions probably gave *Pinus* an edge over *Corylus*. *Corylus* may have remained in the local area, propagating vegetatively. However the decline in *Pinus* at *c.* 9500 cal BP would have offered an open canopy, encouraging flowering by *Corylus*. The absence of an increase in *Corylus* pollen at this time suggests it had been excluded from the area entirely.

Shade tolerant *Vaccinium* (Ritchie, 1956) could have been present after *c.* 9420 cal BP, but the open ground preferring *Empetrum* (Bell and Tallis 1973) is also a component of the understory. *Empetrum* exceeds the 2% TLP threshold used by Binney (1997) to indicate local presence, after *c.* 9500 cal BP. An RSAP of 2m for both *Vaccinium* and *Empetrum* (Bunting 2003, Bunting *et al.* 2004) means both of these taxa were locally present, probably on the basin edges or slopes. *Empetrum* is usually confined to open situations, though it does occur in open pinewoods (Bell and Tallis 1973); *Vaccinium* generally reaches maximum vegetative and reproductive capacity in open pinewoods (Ritchie 1956). Finding the two taxa in combination is suggestive of a woodland edge. *Empetrum* may have occupied the mire margin, outside the canopy. *Vaccinium* was more distal, located under trees on the basin slopes.

Poaceae is common in the pollen assemblage, typically comprising 5 to 10% TLP. Poaceae is regarded as having low pollen productivity (Brostrom *et al.* 2004) and a similar RSAP to *Empetrum* and *Vaccinium* (Bunting 2003, Bunting *et al.* 2004). Huntley and Birks (1983) suggest that Poaceae comprising 10% TLP is indicative of local abundance in wooded sites. Appearances of *Filipendula*, *Potentilla* type and Rosaceae undifferentiated, *Ranunculus*, *Campanula*, *Circaea* and *Melampyrum* together with Poaceae suggest a herb rich grassland.

A dip in the percentage and concentration of Poaceae pollen is coincident with the oscillation in *Betula* pollen suggesting an association between herb rich grassland and *Betula*. If this is the case there may have been a differentiation of vegetation around the basin and on the basin slopes. *Empetrum* could have been found on the edges of the mire with *Vaccinium* further back from the mire margin on the basin slopes. Poaceae could have been an associate of both *Empetrum* and *Vaccinium*. *Betula* grew on the basin slopes but in so doing tended to exclude *Pinus* for much of the time, preventing pine trees from shedding needles directly into the mire.

lpaz DB2a, 115-171cm, *c.* 5850-9200 cal BP

Pinus sylvestris- Betula- Cyperaceae- Poaceae

Basin environment

The mire surface probably became drier within this zone, with at least some periods of time with little or no surface water. Aquatics diminish to a single appearance of *Potamogeton* at *c.* 6454 cal BP. Algal types 58 and 60, indicative of open water (van Geel 1978) are only found at *c.* 6330, 7240, 7740 and 9060 cal BP. Cyperaceae nearly disappear between *c.* 7050 and 7820 cal BP and typically comprise around 5% TLP elsewhere, but there are several appearances of *Caltha* type pollen, most likely to be *Caltha palustris*, (marsh marigold). *Filipendula*, reported as clearly associated with moist soils and the margins of open water by Preston *et al.* (2002), decline, particularly after *c.* 6840 cal BP. Diatoms appear for the first time in this zone. Presence or absence of diatoms is an indicator of presence or absence of open water, but higher values before *c.* 8650 and after *c.* 7490 cal BP do not necessarily indicate deeper water or lower seasonal variation.

Sediment type is initially almost unchanged from DB1 to DB2a, with just a slight decrease in identifiable plant material. Percentage LOI (Figure 4.2) begins to fall at the base of the zone and drops below 80% after *c.* 8200 cal BP. Percentage light transmission (Figure 4.2) is not in agreement with other indicators of mire surface wetness. Inferences of increased surface wetness (upward trends in light transmission) between *c.* 7450 and 7800 cal BP, and decreased surface wetness (downward trending light transmission) between *c.* 6050 and 7350 cal BP, does not correlate with other proxies. Light transmission stays consistently above 50% only after *c*. 6000 cal BP. Changes in light transmission correlate well with changes in LOI, and may therefore be related to decreases in humic acid as the proportion of organic matter falls.

The sedimentary environment begins to change from *c.* 8200 cal BP as the balance between organic and inorganic content changes. Declines in Cyperaceae and *Filipendula* are indicative of decreased organic production. If the modern analogy of seasonal drying of relatively shallow water in the basin is valid organic accumulation from algae could also decline and at the same time as organic accumulation decreases, inorganic accumulation increases. Mineral material could also be allochthonous, from the basin slopes, from unstable or incompletely vegetated basin slopes, or it could be autochthonous, as a result of mineralization of the peat surface.

Mineralization of the peat surface would be expected to result in increased pollen corrosion, which is not apparent. However the proportion of degraded pollen does not change greatly anywhere in the sequence and there is little evidence of increased instability of the basin slope. Apiaceae, a varied group, including taxa regarded as indicative of disturbance, is slightly more important before *c.* 8100 cal BP, *Cirsium* appears a few times in this zone and even the more definite increase in the consistency of *Pteridium aquilinum* is not strong evidence of instability.

If the analogy of a drying peat surface is sound, regional climate dried gradually over *c.* 4000 cal years. Conversely if mineral accumulation from the basin slopes increased this happened very gradually over the same long period, but with no indication of decreased organic accumulation, an increase in sediment accumulation rate would also be expected. This is not supported by the dating model, making drying of the peat surface more likely.

Fire

As in lpaz DB1 the charcoal proportions are low. There is weak evidence of local fire at *c.* 8650 cal BP when all particles are larger than 50μm and most (9 of 15 particles) are larger than 75μm. Low charcoal counts make any conclusion unreliable. There are very small peaks of charcoal at *c.* 5930 and between *c.* 6450 and 6330 cal BP. Totals in each of these peaks is less than 50 particles, but increases occur in all size categories, increasing the likelihood of small local fire(s). No levels contain particles larger than 150μm and the consistently low totals make any conclusions using the ratio of large to small particles tentative.

Vegetation

The arboreal pollen component (mainly *Betula* and *Pinus*) comprises around 80% TLP for much of this zone. Although model-based vegetation reconstructions using AP/NAP ratios tend to underestimate vegetation openness (Brostrom *et al.* 1998, Sugita *et al.* 1999, Sugita 2007, Soepdoer and Lotter 2009), in this case it is reasonable to follow O'Sullivan (1974a), Binney (1997) and Shaw (2006) and conclude that there was a closed canopy. Influx exceeds the 2000 grains cm^{-2} $year^{-1}$ found by Jensen *et al.* (2007) and is close to the value found by Hattestrand *et al.* (2008) to indicate dense pine woodland.

The abrupt rise of *Pinus* percentages at the base of the zone indicates an expansion of *Pinus* in the area. *Pinus* stomata are present in all but two levels (*c.* 7740 and 6060 cal BP) with values up to 5% TLP plus stomata. *Betula* values fall to 10-15% TLP, about the value found by Shaw (2006) to indicate local presence, by *c.* 8430 cal BP and concentration curves for *Pinus* and *Betula* also rise and fall respectively. *Betula* could have been present locally in gaps within the *Pinus* canopy, or in larger numbers on the valley sides.

Quercus percentages increase slightly in the middle of the zone (to 2-3% TLP). Shaw (2006) found *Quercus* within 20m of surface samples with similar percentage representation (Shaw 2006, section 6.5.3), but an extra-local presence or regional increase is more likely. At 1% TLP or less *Alnus* was not present locally. This low percentage does not give any reason to suggest that the modern altitudinal limit to flowering, 320m (McVean 1955a), was different. *Ulmus* pollen is sporadically present, typically with only 1 or 2 grains per level. Anderson (1970) found *Ulmus* to be a low pollen producer but Shaw (2006) found single grains in modern samples in areas with no local tree presence. *Ulmus* is most likely to have been part of the regional component of pollen rain, with no local occurrences.

Salix declined compared to DB1 but is still likely to have been locally present, probably in the same locations as in DB1, drying of the mire surface may have enabled this taxa to encroach on to the mire itself, but seemingly not in large numbers. *Corylus* is present as in DB1, either in canopy gaps with *Betula* or with *Salix*.

Poaceae was diminished but still locally present with many of the herbs found in DB1. There are other indicators of open conditions or disturbance in the pollen assemblage, Apiaceae is common before *c.* 8100 cal BP and there are occasional appearances of *Pteridium aquilinum*. These support the interpretation of a partially open canopy over the site and consistent appearances of *Juniperus* type (between *c.* 8430 and 6480 cal BP) are also in agreement with an opening canopy within and around the basin.

Calluna is also an indicator of more open woodland, struggling to thrive when light levels fall below 40% of open ground (Gimingham 1960), making growth under dense tree canopy unlikely. Consistently low values (1-2%) of *Calluna* are in agreement with local presence, but local presence of *Empetrum* and *Vaccinium* is less likely; *Empetrum* does not exceed 2% TLP, the threshold used by Binney (1997), and *Vaccinium* is only sporadically present at very low percentages. Even allowing for the slightly higher pollen productivity of *Calluna* compared to *Empetrum* and *Vaccinium* (Brostrom *et al.* 2004) the similar RSAP of the three taxa leaves local presence of *Calluna* more likely (Bunting 2003). As in DB1 the variation between the percentages of each taxon, together with their ecological preferences suggests that vegetation was differentiated around the basin. The slightly higher and more consistent percentages of *Calluna* make a proximal position around the mire likely, with *Vaccinium* tending to grow as before, more distally, on the basin slopes. The typical British form of *Calluna*, a ‘semi-sedentary dwarf shrub’ (Gimingham 1960), may have prevented *Empetrum* from successful growth on some or all of the basin area. Unlike DB1, however, *Pinus* was directly over the mire surface for most of the zone. This means that the areas around the mire with strong enough light for *Calluna* (or *Empetrum*) to have thrived will have been limited.

Dwarf shrubs remain a minor percentage of the pollen assemblage throughout the zone, but concentration increases slightly, especially after *c.* 6480 cal BP. The low percentages and concentrations make dwarf shrubs a relatively minor component of the vegetation assemblage; this may be an indication of relatively bare slopes becoming increasingly covered through the zone. Grime *et al.* (2007) report that *Empetrum* and *Vaccinium* are found mainly in areas with little exposed soil, though *Calluna* is found across a wide range of surfaces.

It is probable that the mire surface at Doire Bhraghad formed a slightly more open section in the canopy. The three heath taxa may have occupied the basin differentially, with *Calluna* and *Empetrum* growing in open conditions and *Vaccinium,* able to tolerate lower light conditions (Ritchie 1956), occupying ground under the canopy. This distribution of vegetation can occur in *Pinus* woodland today when vegetation is relatively undisturbed (Figure 4.6). Poaceae is found together with all three heaths and herbs such as *Filipendula* and *Potentilla* are most likely to be present around the edges of the mire.

Woodland appears to have been relatively stable for *c.* 3000 cal years, though there is evidence of change in the field layer from *c.* 6480 cal BP, such stability is often regarded as beneficial for increased biodiversity. The initial decline in palynological richness is in agreement with a closing canopy, but need not necessarily imply a decrease in biodiversity of the assemblages. A closing canopy results in a decreased pollen source area for the site (Seppa 1998, vad Odgaard 1999, Berglund *et al.* 2008), extra-local pollen taxa are excluded, lowering richness. However the occurrence of rare or low pollen producing taxa in the pollen assemblage is a stronger indication of local presence within the vegetation. The increase in palynological richness in two levels after *c.* 7240 cal BP comes in the middle of this relatively stable period. This increase in palynological richness is likely to correlate with an increase of species richness in the vegetation.

lpaz DB2b, 101-115cm, *c.* 4910-5850 cal BP

Pinus sylvestris

Basin environment

The minerogenic band represents an abrupt decrease in the proportion of organic matter in the sediment, continuing the trend from lpaz DB2a. Sediment accumulation also decreases slightly, (Table 4.2 and Figure 4.5). As before, an extended seasonal dry period could explain the decrease in the organic fraction of the sediment. If this mechanism is responsible, the very low LOI percentage suggests that the mire surface was dry for much of the year, more than the 4-5 months seen today. It is possible that the water table dropped slightly or that the mire surface rose above the water table, allowing the surface to dry out.

There is some palynological evidence supporting continued drying of the mire surface. There are no Aquatic taxa identified, and percentages and concentrations of Cyperaceae pollen continue to decline. *Filipendula* disappears entirely, suggesting drying of the mire, or even disappearance of open water (Preston *et al*. 2002). *Sphagnum* does not have high percentages within this zone but is consistently present for the first time, suggesting not only damp mire surface conditions but also changes to the way organic matter accumulated. There are still algal remains associated with open water (van Geel 1978) between *c*. 5390 and 5660 cal BP. Corroded pollen, associated with aerobic conditions, decreases in both indeterminable (Figure A.1a) and determinable sums (Figure 4.7), suggesting surface wetness is unchanged. Diatoms are absent; pollen preparation required treatment with Hydrofluoric Acid to remove the high mineral content.

Figure 4.6 Mature *Pinus* woodland in Glen Quoich. To the right of the picture *Pinus* canopy is denser and casts enough shade to favour the growth of *Vaccinium*. To the left of the picture the open space allows the growth of *Calluna*.

Palynological evidence supporting basin slope instability has declined, making an increase of allochthonous mineral material less likely. *Pteridium aquilinum* disappears from the assemblage and *Empetrum* and *Vaccinium*, associated with habitats with relatively little bare soil (Grime *et al.* 2007), increase. Decreases in indeterminate crumpled or folded and split pollen between *c.* 4910 and 9200 cal BP (Figure A.1a), are not consistent but do not support a change to the rate or origin of mineral matter. The increase in determined split pollen is entirely due to increased *Pinus* abundance (Figure 4.7). There is no increase in the proportion of split *Pinus* pollen.

The consistency of particle size distributions (Figure 4.3) is in agreement with similar deposition processes throughout lpaz DB2b, though this cannot be extended to include lpaz DB2a. If mineral material is derived from allochthonous input, the small particle sizes of mineral sediments in the minerogenic band indicate low energy transport.

A simple solution to the evidence involves a gradual decline in organic accumulation, followed by virtual cessation and then slightly more rapid increase in organic accumulation. During this time there was a steady input of inorganic material from the basin slopes, as organic accumulation varied, the relative importance of the inorganic fraction changed, however it is likely that processes affecting the Doire Bhraghad basin are more complicated.

Fire

Charcoal still shows very low abundance. There are no levels with large particles, and the only level with a high ratio of large to small particles (112cm, *c.* 5660 cal BP) is from a total count of six charcoal particles, too low to give a reliable conclusion.

Vegetation

Pinus dominates the pollen assemblage with up to 80% TLP, indicating a closed canopy (O'Sullivan 1974a, Shaw 2006). Pollen influx is highest in this zone, with *Pinus* exceeding 3000 grains cm^{-2} year^{-1}. Pine stomata are absent from all levels within this zone. An extended count of stomata, based on counts of exotics, shows that there are no stomata to the equivalent of a pollen count of between 2500-4000 grains: no trees were able to shed needles onto the mire surface. Increases in *Pinus* percentage and influx, in conjunction with the disappearance of stomata, suggest a disagreement between evidence concerning the nature of the woodland or indicate an extended woodland clearing.

The woodland in lpaz DB2b was probably exclusively *Pinus.* At the base of the zone *Betula* concentrations and influx increase before declining steadily to the top of the zone; *Betula* percentage decreases to less than 5% TLP by the top of the zone, indicating local disappearance according to Shaw (2006). This change may explain the very long (*c.* 700-800 cal years) absence of *Pinus* from the basin, as shown by disappearance of stomata. Temporary colonisation by *Betula* of an opening in the otherwise closed *Pinus* canopy could prevent deposition of stomata, but the absence of pine stomata could also be an effect of reduced preservation. *Alnus* influx and concentration values increase at the base of the zone but percentages remain low. The increases are interpreted as a regional increase in *Alnus,* not to altitudes high enough to suggest local growth or presence significantly but higher than the current altitudinal limit of *c.* 320m (McVean 1955a). Percentages of *Quercus* and *Ulmus* are unchanged, increased concentrations are also extra-local.

This increase in evidence of woodland taxa seems to reinforce the conundrum between a closed exclusively *Pinus* canopy and absence of *Pinus* over the mire itself. Increased input of extra local and regional taxa is in agreement with an opening in the canopy, which might favour *Betula*. The length of time during which *Pinus* is apparently unable to occupy any position around the mire certainly requires a reason, especially as all other indicators suggest a very dense pine canopy.

Vaccinium and *Calluna* increase slightly in both percentage and concentration diagrams (Figure A.1a and b). The tolerance of *Vaccinium* for lower light conditions (Ritchie 1956) is in agreement with a closing *Pinus* canopy but the increase in *Calluna* suggests open conditions (Gimingham 1960). *Empetrum* does not exceed Binney's (1997) 2% TLP threshold but may still have been found on basin slopes. This is in agreement with a less dense canopy centred around the mire surface.

Although dwarf shrubs are relatively unimportant, they may be common enough to prevent growth by *Pinus* directly over the mire surface. Local competitive interactions between *Pinus* and e.g. *Empetrum* (Zachrisson *et al.* 1996, Read *et al.* 2004, Nilsson and Wardle 2005) or prevention of seed germination by a moss mat (McVean 1963a, Crawford 2008) can delay colonisation by *Pinus*. Zachrisson *et al.* (1996) and Read *et al.* (2004) found that fire helped remove the phenolic compounds produced by some Ericoid species that can inhibit *Pinus* mycorrhiza. With no evidence of local fire for several thousand years it is possible that these compounds could have built up in the substrate surrounding the Doire Bhraghad mire. Dwarf shrubs and mosses may also prevent *Pinus* colonisation by physically interrupting access by the seeds to the substrate (Malmer *et al.* 1994, Crawford 2008). A combination of *Betula* colonisation and interference with *Pinus* regeneration by understory taxa may have been enough evidence to exclude pine trees.

Palynological richness is comparable to levels in lpaz DB2a but much more variable. The percentage of arboreal taxa remains similar, but variations in influx suggests change to the canopy. This could result in change to the pollen source area giving the variation in palynological richness, rather than variation in local vegetation diversity. Opening of the local canopy, temporary colonisation by *Betula* and modest increases in

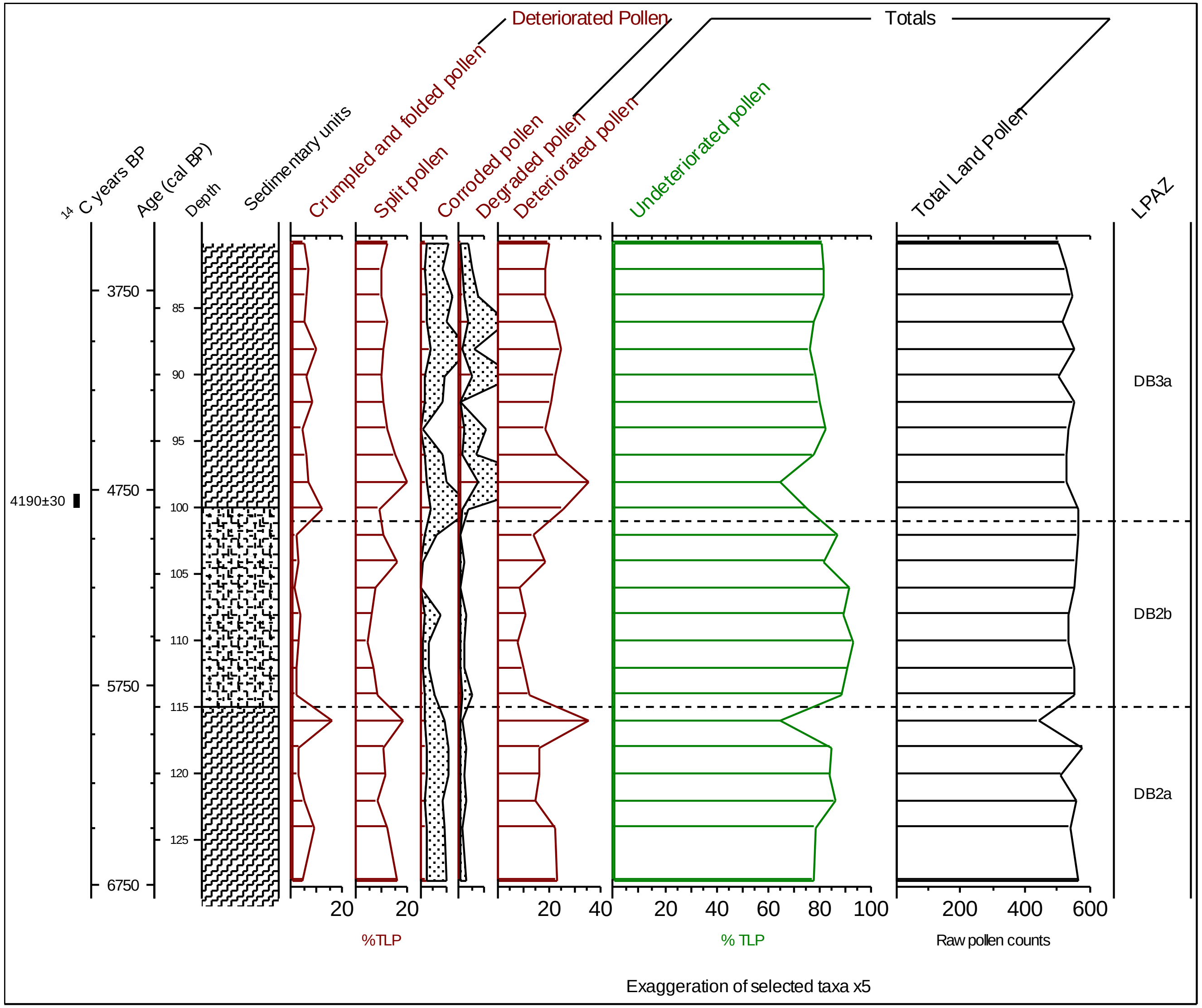


Figure 4.7 Normal and deteriorated pollen between 130 and 80cm

heath taxa would be in agreement with both the disappearance of very local pine and the changes in palynological richness.

lpaz DB3a, 71-101cm, *c.* 4910-2940 cal BP

Pinus sylvestris*-Poaceae-*Calluna vulgaris*-*Quercus

Basin environment

Lpaz DB3a shows a gradual return to highly organic sediment accumulation in the basin. LOI analyses indicate that organic content returns to high levels (more than 80%) by *c.* 3970 cal BP. Colorimetric light transmission decreases, dropping below 30% by about the same time. As noted above, variations in light transmission may correlate with organic content. There are relatively high counts of diatoms in every level in lpaz DB3a, but Hydrofluoric Acid treatment was no longer necessary in pollen preparation. There are two occurrences (72 and 98cm) of algal type (type 58) associated with open water by van Geel (1978). Cyperaceae are slightly increased compared to DB2b, but are still relatively unimportant. Small increases in *Salix*, especially after *c.* 3370 cal BP, might also indicate a return to a wetter mire surface. Although at low percentages, *Sphagnum* is present consistently for the first time, suggesting a change to accumulation as a *Sphagnum* mire.

The extended period of lowered LOI percentages make regional changes less likely to be responsible for the change in accumulation, but does not provide a reason for changes to the balance between mineral and organic content. Mineral material could still be from either allochthonous input or mineralization, or the absolute accumulation of organic could be changing. Differentiation between these processes could be aided by reference to the Geldie Lodge sequence and evidence from elsewhere in the Cairngorms and Scotland. This question will be addressed again in Section 7.10.

Fire

There is an abrupt change in the fire regime at the base of lpaz DB3a. The percentages of charcoal increase in all class sizes, but there are especially large quantities of particles less than 50µm in size. Counts decrease after *c.* 3900 cal BP (86cm), but remain high enough for an increase in the ratio of large to small particles, which occurs after this, to be meaningful (Figure A.1d). This may indicate that fires were closer to the core site in levels above *c.* 3900 cal BP (Clark and Royall 1995). There are very large particles (Table 4.8), indicating fires within 100m of the site (Clark 1988, Peters and Higuera 2005), at *c.* 3130, 3900 and 4710 cal BP (74, 86 and 98cm).

Table 4.4 Large charcoal particles found within DB3a

Stratigraphic level (cm)	Length of longest axis (µm)	Total number of micro-charcoal particles	Ratio of large to small particles
74	200	107	0.24
86	120, 250 x2, 260	226	0.44
98	350	330	0.14

Vegetation

Pinus is the dominant pollen taxon and stomata are present in most levels; *Pinus* remained important around the mire but the canopy began to fragment. Change to the canopy structure and the occurrence of stomata correlate with peaks in charcoal. There are no other trees locally present, increases in proportions of dwarf shrubs are relatively modest but Poaceae is important under the fragmenting canopy. Increases in Poaceae also correlate with changes in the fire regime.

The reappearance of stomata from *c.* 4700 cal BP coincides with a possible local fire event (Table 4.2). The percentage of *Pinus* halves (80 to 40% TLP) for a single level at *c.* 4840 cal BP, coincident with the initial increase of charcoal counts. The percentage of *Pinus* recovers to slightly lower values compared to the previous zone, but both concentration and influx of *Pinus* fall abruptly from *c.* 4840 cal BP. Influx and concentration briefly recover and increase but after a second decline (*c.* 4170 cal BP) both remain low. *Pinus* influx drops to around 800 grains cm^{-2} year^{-1}, below both Hattestrand *et al.*'s (2008) and Jensen *et al.*'s (2006) influx for dense *Pinus* woodland.

The collapse in *Pinus* concentration and influx, combined with only a slight fall in *Pinus* percentages and the presence of stomata suggests that *Pinus* remained within the basin but suffered fragmentation in the wider landscape. The combination of values also shows changes to be indicative of woodland fragmentation rather than the substitution of *Pinus* by other tree taxa. *Betula* is slightly increased, but only reaches percentages indicating local presence after *c.* 3130 cal BP; *Betula* is likely to have been present within the valley but probably on the valley sides. *Quercus* increases to over 5% TLP in lpaz DB3a, between the values regarded as indicative of local presence by Shaw (2006), 10% TLP, and Huntley and Birks (1983), 2% TLP. This may represent local presence but is more likely to be from extra-local sources, especially as a thinning canopy would result in an increasing pollen source area for the basin (Sugita *et al.* 1999, Bunting 2003). *Salix* may have been slightly more prevalent than in DB2b, but was not an important component of the assemblage. Increases in *Populus*, *Sorbus* and *Corylus* are too small to indicate change to the vegetation assemblage.

Increases in *Calluna* and especially Poaceae (15% TLP) are strong evidence for thinning *Pinus* woodland. Sporadic appearances of *Juniperus* type, and presence of *Empetrum* at around 2% TLP also suggest an opening canopy. Total pollen influx is very low for most of DB3b, suggesting that the plant communities replacing *Pinus* were patchy, sparse or mainly low pollen producers, which would include Poaceae (Brostrom *et al.* 2004). Prevalence of Poaceae in the pollen assemblage confirms that fragmentation was mainly as a result of the increase of grassy openings rather than of heaths or shrubs.

The peaks in percentage, influx and concentration of Poaceae coincide with a charcoal peak at *c.* 4840 cal BP and high charcoal counts from *c.* 4300 to 3770 cal BP. It is probable that the prevalence of Poaceae in the vegetation assemblage was a combination of continued fire and activity by grazing animals. Grazing could have been by domesticated, semi-domesticated or wild animals. Disturbance of this kind is supported by the first appearance of *P. lanceolata* and the reappearance of *Potentilla* type, though Mazier *et al.* (2006) suggest that these taxa are indicative of human activity at a regional rather than local scale. The low percentages of both taxa are in agreement with this interpretation.

Changes to tree canopy density, causing variations in pollen source area and other disturbances to vegetation, may be reflected in the rapid but directionless changes in palynological richness. A rapid decline (30.5-21.6), between *c.* 4300 and 4710 cal BP occurs as *Pinus* influx recovers (from about 1000-1400 grains cm^{-2} yr^{-1}). The subsequent section of relatively high fluctuating values (32.5-26.8) coincides with the high *Pinus* percentages that occur after the second collapse in influx and concentration. These values may reflect variation in long distance pollen inputs rather than in local input.

lpaz DB3b, 58-71 cm, *c.* 2170-2940 cal BP

Pinus sylvestris*-Poaceae-*Calluna vulgaris-Sphagnum

Basin environment

Cyperaceae percentages and concentrations increase slightly within this zone, *Sphagnum* proportions also increase, but those of open water decline. Diatoms disappear by the top of the zone and algal types (type 60, van Geel 1978) indicating open water are identified only at *c.* 2510 cal BP. The increase of *Sphagnum* may represent the initiation of a raised moss, as seen in the centre of the basin today, raising the mire surface away from the water table. Growth of this is important to interpretation, as in the present mire it provides the substrate occupied by *Pinus*.

Increasing LOI suggests a return to the depositional conditions before lpaz DB2b. As already noted this may indicate that conditions in the basin are becoming wetter or that the basin slopes have stabilised reducing the input of inorganic material.

Fire

The zone opens with a large peak of charcoal, skewed to smaller particles (less than 50μm), but there are no levels with large particles of charcoal. There is no significant increase in the ratio of large to small particles, so no evidence to suggest more local fire. The quantity of micro-charcoal in the assemblage suggests that fire was important in the extra-local or regional landscape.

Vegetation

The fragmentation of the woodland, which began in lpaz DB3a continues in lpaz DB3b. *Pinus* was still important in the landscape, with concentration and influx values similar to those in lpaz DB3a and stomata present in all levels. *Pinus* percentages now decline, with *Calluna* and Poaceae being the main taxa increasing as a result. Percentages of *Empetrum* and *Vaccinium* also increase but those of *Juniperus* are no longer so important. *Betula* continues to show similar or slightly increased percentages; presence on valley sides is still most likely. The percentage of *Quercus* pollen has declined and can no longer be regarded as even potentially local.

As in lpaz DB3a, defining the density of the *Pinus* canopy is difficult as evidence is contradictory. *Pinus* percentages exceed 40% TLP for all of lpaz DB3b, suggesting a relatively dense canopy (O’Sullivan 1974a, Shaw 2006) but declining influx values (from about 1000 to 500 grains cm^{-2} yr^{-1}) better reflect open woodland (Seppa and Hicks 2006, Jensen *et al.* 2007). Declines in concentration probably also reflect an open woodland. The relatively high totals of arboreal pollen throughout lpaz DB3a are in agreement with the findings of Sugita *et al.* (1999) and Sugita (2007) that models of AP/NAP ratio tend to underestimate canopy openness. The high percentages of stomata may only be indicative of a few trees, or even a single individual, growing over the mire.

Poaceae was an important component of the vegetation with two peaks of over 15% TLP at *c.* 4040 and 4710 cal BP, and percentages over 10% TLP throughout the zone. This may indicate that openings in the *Pinus* canopy were populated by grasses, or that they were locally more important, within the basin. Midway through DB3b, *Empetrum* values exceed the 2% TLP used by Binney (1997) to indicate local presence, indicating an opening canopy. *Calluna* increases rapidly through the zone, also suggesting an opening canopy (McConnell and Legg 1994). The greater importance of Poaceae compared to *Calluna* could show that the canopy was dense enough to maintain light below the 40% of open ground intensity reported by Gimingham (1960) as delimiting growth for *Calluna*, but the persistence of Poaceae may also indicate grazing by animals.

Palynological richness is less variable than the preceding zones and is relatively high, especially compared to those in closed *Pinus* woodland earlier. This may also be suggestive of fragmented woodland (vad Odgaard 1999). The open canopy allows input from rarer, lower pollen producers (Birks and Line 1991), from extra-local and regional sources. Higher, more stable palynological richness may also reflect vegetation mosaics, perhaps in the form of isolated woodland patches rather than scattered individual trees.

lpaz DB4, 4-58cm, *c.* 50-2170 cal BP

Calluna vulgaris- Sphagnum- Vaccinium- Empetrum

Basin environment

The large peak in *Sphagnum* is a clear indication of the growth of a raised, drier peat in the western half of the basin. Algal remains associated with open water (van Geel, 1978), are identified at *c.* 1320 and 2050 cal BP, but diatoms are absent from the zone and Cyperaceae remain unimportant.

LOI remains high, typically in excess of 90%. Light transmission remains low in agreement with strong autochthonous production of organic matter. Both these data are in agreement with increases in *Sphagnum* but suggest that onset of the *Sphagnum* mire did not necessarily include open water.

Fire

There are very large numbers of charcoal particles in this zone, mostly within smaller classes, indicating fire more distal to the sample site. There are no very large particles and the ratio of large to small particles does not change greatly (Figure A.1d), giving no compelling evidence to suggest fire affecting the local vegetation.

Vegetation

At the base of the zone *Pinus* percentages drop below 20% TLP, staying below this value for the whole zone. With concentration and influx also decreasing, the transition to scattered trees within a heath dominated by *Calluna* is complete. *Pinus* influx drops below 200 grains cm^{-2} year^{-1}, the lower limit of Jensen *et al.*'s (2007) estimate for open *Pinus* woodland (200-400 grains cm^{-2} year^{-1}). Stomata disappear at the base of the zone but reappear after *c.* 440 cal BP.

Presence of stomata from *c.* 440 cal BP suggests that the two extant *Pinus* individuals growing in the Doire Bhraghad basin (Figure 3.6) are not the first generation of current growth in the basin. The slight increases in percentage, concentration and influx at the surface are likely to relate mainly to trees within the basin, but may also reflect extra-local or regional woodland. The declines in charcoal are coincident with increases in *Pinus,* perhaps showing decreased fire in the landscape favouring resurgence of *Pinus*. *Betula* is further diminished in importance and other arboreal taxa, *Quercus, Ulmus* and *Alnus* remain unimportant.

The *Calluna* dominated heath probably retained scattered trees and included *Empetrum* and *Vaccinium* within the basin. *M. gale* is important before *c.* 1320 cal BP, probably growing on the mire surface or just to the south of the mire. *E. cinerea* and *E. tetralix* are slightly more important in this zone, but still relatively rare, *Juniperus* is present only at *c.* 1320 cal BP, preceding the resurgence of *Pinus*. Tree cover may be dense enough to prevent further local growth of *Juniperus* and *M. gale*.

There is little evidence of human activity. *P. lanceolata* is present at very low percentages at *c.* 1320 cal BP and the surface level. The high percentages of Poaceae in the previous zones, interpretable as evidence of grazing, are not a feature of DB4. There are no occurrences of cereal type grains, but *Urtica* is present at *c.* 1620 cal BP; the very low percentage in a single level is not a conclusive indicator of human activity. Charcoal decreases and increases in *Pinus* percentages may also be related to a decline in the human impact within the valley.

Low palynological richness probably reflects the decline in the mosaic pattern of vegetation as trees became increasingly scattered and heaths increasingly dominant. A slight increase in palynological richness after *c.* 440 cal BP, as *Pinus* increases, would be in agreement with an increase in the patchiness of the vegetation.

5 White Bridge: results and interpretation

5.1 Introduction

The results and the interpretation of the results from the White Bridge core are presented here. Data including sediment descriptions and morphology, colorimetric data, percentage loss of mass on ignition (LOI) and radiocarbon assays are presented in Section 5.2. Descriptions of local pollen assemblage zones are presented in Section 5.3.1 and results of rarefaction analysis (palynological richness) are presented in Section 5.3.2. Dating models and pollen influx data are presented and described in Section 5.4. Interpretations of the White Bridge data form the final section of this chapter (Section 5.5). All pollen diagrams are presented in Appendix A.2.

5.2. Sediment description and morphology, colorimetric data, percentage loss of mass on ignition and radiocarbon assays

The sediment stratigraphy at White Bridge is described in Table 5.1. The sediment consists of poorly consolidated peat with large quantities of plant material overlying more consolidated basal sediment. Sediment below 108cm is rich in inorganic material: silt and clay is common but there are no sand-sized particles. Visual inspection for Troels-Smith description revealed two thin (less than 1mm thick) layers of inorganic material at 14 and 44cm, but apart from these the sequence above 100cm is entirely organic. Colour lightens from dark brown at the base of the sequence to dark yellow at the top.

Investigation of the mire stratigraphy using an Eijkelkamp corer (Section 3.3) revealed that this stratigraphy was typical of the palaeochannel. Detailed cross sections of the peat immediately surrounding the core site are presented in Figure 5.1.

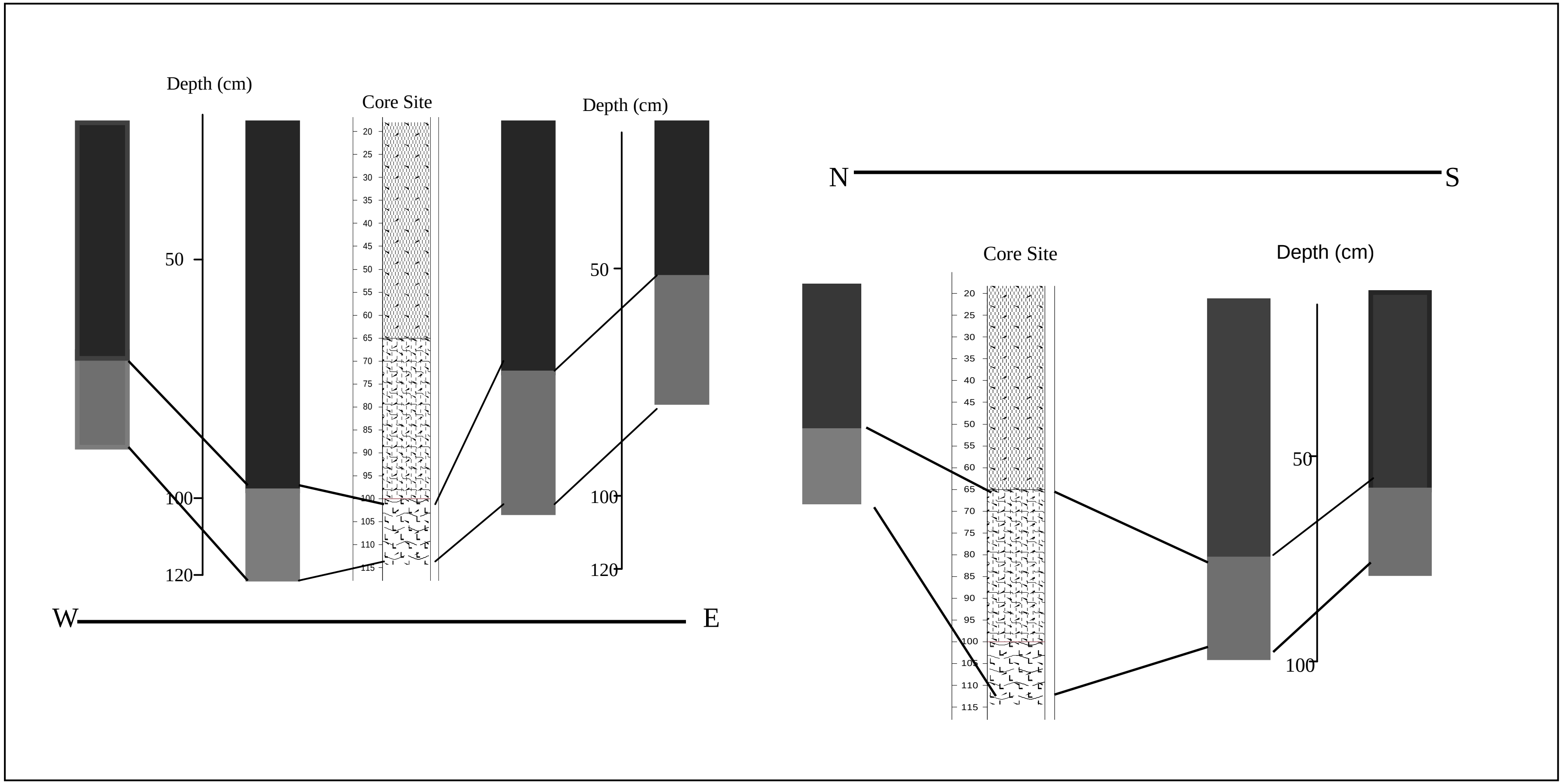


Figure 5.1 Peat cross sections, White Bridge. The depth of the basal inorganic rich component of the peat is shown as a lighter coloured section in each column, the changing depth of the sedimentary transition is correlated with the full Troels-Smith symbology of the core sequence itself. Columns are at 5m intervals on the east-west transect and 2m intervals on the north-south transect.

Table 5.1 White Bridge sediment description

Depth (cm)	Colour	Description	Troels-Smith classification
0-12	Light brown- dark yellow	Very loose sedge peat.	Th4
12-65	Mid brown	Loose sedge peat, occasional minerogenic material (44 and 14cm).	Th (Phra)3 Dh1 (As+ Ag+)
65-100	Dark brown to mid brown.	Loose sedge peat with clearly identifiable vegetation. Colour lightens upwards.	Th1 Tb1 Dh2.
100-114.5	Dark brown,	Well consolidated mineral and organic detritus. Silt decreases upwards.	Ag1 As1Dh+1 Tb+1.

Colorimetric data and percentage LOI are presented in Figure 5.1. Above about 16cm and below about 90cm there is an inverse relationship between LOI and humification data. Between these levels peat has LOI values typically greater than 80% but this high carbon content is interrupted at several points, mostly as single level incursions. From about 55 and 35cm this changes as half of the levels are at or below 80% carbon.

Transmission values between 90 and 56cm vary from 70 to 30%, but show no directional change. From 54 to 40cm there are a series of low values (20-30%). Above 40cm a brief rise in transmission to between 46 and 52% is followed by a gradual increase from low (around 30%) to mid values (around 50%) at 14cm.

There are two radiocarbon assays available for White Bridge, these are presented in Table 5.2. There are no additional dating correlations in the pollen stratigraphy.

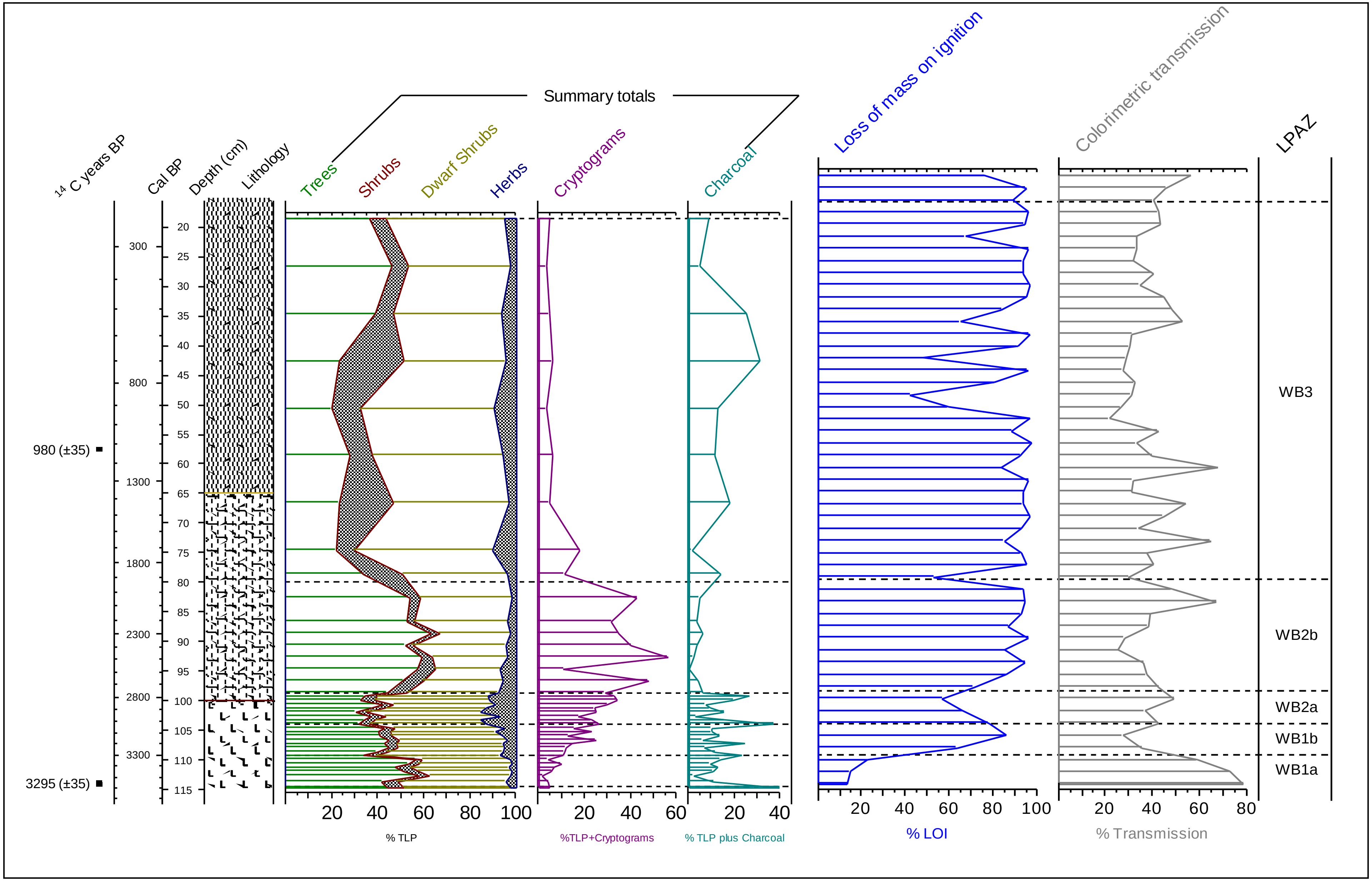


Figure 5.2 White Bridge percentage loss of mass on ignition and percentage colorimetric transmission, with summary percentage pollen diagrams

Table 5.2 Results of radiocarbon assays for White Bridge

			Radiocarbon age	Loss of mass on ignition	$\delta^{13}C_{PDB}$	Calibrated age ±2σ using OxCal 3.1	
Laboratory code	Sample code	Depth (cm)	years BP ±1σ	(% LOI)	‰ ± 0.1	Range, cal years BP,	Midpoint, cal BP
GU-12649	WB2	57-58	980 ±35	97	-26.9	1160-990	1075
GU-12648	WB1	113.5-114.5	3295 ±35	13-14	-27.2	3690-3490	3590

5.3 Descriptions of pollen assemblage zones and rarefaction analysis

5.3.1 Description of pollen assemblage zones

The White Bridge sequence is divided into three local pollen assemblage zones (lpaz), WB1-3, two of which are subdivided (WB1, WB2), marking major and minor changes in the pollen stratigraphy interpreted from stratified cluster analysis implemented via CONISS (Grimm 1987). Descriptions of local pollen assemblage zones are presented below. Diagrams showing percentage and concentration data are presented in Appendix A.

lpaz WB1a, 109.5-114.5cm, *Pinus sylvestris-Calluna vulgaris-Betula*

Radiocarbon assay, 113.5-114.5cm, 3295±35 years BP

The percentage of *Pinus* is at around 30% TLP at the beginning of the zone. There are two peaks (around 50% TLP) at 112.5 and 109.8cm, the trough between drops to 40% TLP. Pine stomata are present in two levels, 114.5 and 111.1cm. *Betula* comprises 7.5% TLP at the start of the zone but declines slightly to 5% TLP by the top of the zone. *Alnus* also declines, from about 5% to 1% TLP. *Quercus* and *Ulmus* are present at 110.5 and 112.5cm and 110.5cm and 113.5cm, respectively. *Corylus* shows a slight peak at 111cm (3% TLP) but drops to less than 1% TLP at the top of zone. *Corylus avellana* type has percentages of just below 5% TLP for the whole zone but shows no directional change. *Myrica* is present in all levels in this zone at low percentages (2% TLP or less).

At the base of the zone, *Calluna* percentage is at 12% TLP, rising to about 18% TLP at the top of the zone; *Empetrum* also increases, from 3 to 5% TLP. The decrease by *Vaccinium*, from 10% TLP at the base of the zone, to 5% TLP at the top of the zone, is interrupted by an increase to 10% TLP from 112.5-111.5cm. *E. tetralix* is absent from the lowest level but is present at 3-4% TLP for the rest of the zone. Ericaceae undifferentiated shows a similar pattern, declining from about 20% TLP to about 10% TLP.

Poaceae is present consistently at less than 5% TLP throughout the zone, Cyperaceae is also consistently present, at 1% TLP or less. *Filipendula* is present in three levels in this zone (110.5, 111.8 and 113.5cm) and Asteraceae is present at 112.5cm.

Sphagnum percentages are low in this zone, less than 10% TLP plus Cryptograms, increasing slightly at the top of the zone. *Polypodium* appears at 110.5, 111.1, 111.8, 112.5 and 114.5cm. Charcoal shows a large percentage peak at 114.5cm (over 40% TLP plus Charcoal), but declines to 5% TLP plus Charcoal at 112.5cm, before increasing to about 20% TLP plus Charcoal at the top of the zone.

lpaz WB1b, 104.4-109.5cm, *Pinus sylvestris-Calluna vulgaris-Betula-Sphagnum-*Poaceae

Pinus percentage fluctuates quite widely in this zone, with troughs at 109.1cm (20% TLP) and 106-105cm (25% TLP). After each trough, percentages increase to

30-40% TLP, but pine stomata are not present in WB1b. The *Alnus* percentage (about 5% TLP) is slightly higher than in WB1a; *Betula* percentage also increases compared to WB1a, to around 10% TLP. *Quercus* pollen is absent from 2 levels, 106.5 and 108.5cm, and reaches 1% TLP only at the top of the zone; *Ulmus* appears less often with a presence at 104.4, 105.8, 107.1 and 107.8cm. *Corylus* pollen is present at less than 1% TLP in all levels except from 107.8-108.5cm, where it reaches 2% TLP. *Corylus avellana* type has percentages of around 5% TLP for the whole zone and *Myrica* percentage increases from about 1% TLP at the base to 2% TLP at the top of the zone.

Calluna percentages are variable. At the base of the zone *Calluna* has a percentage of just under 20% TLP, but increases to 30% TLP at 106.5cm, before declining at the top of the zone. *Empetrum* shows a percentage of about 7% TLP at the start of the zone, but declines to about 3% TLP at the top of the zone. *Vaccinium* has a peak of about 10% TLP from 107.8-109.1cm, and remains consistent at about 6% TLP above that. Ericaceae undifferentiated percentage is variable, less than 5% TLP between 105.8 and 105.1cm but about 15% TLP at 109.1, 106.5 and 104.5cm. *E. tetralix* is present in every level in WB1b, but declines slightly from about 3 to 1% TLP. *A. uva ursa* is present at 104.5, 105.1, 106.5, 107.1, 108.5 and 109.1cm; at 109.1cm, *A. uva ursa* percentage exceeds 1% TLP. *E. cinerea* is present at 104.5, 106.5, 107.8 and 109.1cm.

Poaceae comprises 5% TLP below 106cm, but rises to around 10% TLP above that. Cyperaceae pollen disappears between 107.1 and 107.8cm, but reappears at 106.5cm and increases slightly (to 3% TLP) above that. *Filipendula* is present only at 105.8, 107.8 and 109.1cm.

Sphagnum percentage increases steadily throughout the zone from just over 5% TLP plus Cryptograms at the base of the zone to 25% TLP plus Cryptograms at the top of the zone. Charcoal has a single peak of about 25% TLP plus Charcoal at 106.5, but is about 10% TLP plus Charcoal elsewhere.

lpaz WB2a, 98.6-104.4cm, *Pinus sylvestris*-*Sphagnum*-*Calluna vulgaris*-Poaceae-*Betula*

Pinus percentage fluctuates from 20-30% TLP but concentration declines and pine stomata are absent for most of the zone, present only at 99.1 and 100.5cm. *Betula* percentage increases to over 10% TLP but concentration declines steadily; *Alnus* percentage is always less than 5% TLP, with low and declining concentration. *Quercus* and *Ulmus* have similar percentages to WB1a and B. *Corylus* and *Myrica* have percentages of less than 2%, *Corylus avellana* type is less than 5% TLP. *Salix* appears sporadically at very low percentages (less than 1% TLP).

Calluna percentages fluctuate from 20 to 30% TLP but concentration declines. *Empetrum* increases from about 2 to 5% TLP but *Vaccinium*, fluctuating around 7-8% TLP, has a single level increase to over 10% TLP at 99.8cm. *A. uva ursa* and *E. cinerea* are present in many levels at very low percentages and *E. tetralix* is present in every level at up to 3% TLP. *Phyllodoce* is consistently present and *Pyrola* type is present in several levels.

Poaceae percentage peaks at over 10% TLP below 101.8cm and remains at over 5% TLP above that; Cyperaceae is at 2-3% TLP throughout. Above its first appearance at 109.1cm, *P. lanceolata* appears in most levels. *Filipendula* pollen is also consistently present throughout the zone at up to 2% TLP. Chenopodiaceae, Asteraceae, *Potentilla* type and *Artemisia* are consistently present only in this zone.

Sphagnum percentages continue the trend of WB1a and 1b, in this zone percentage rises to about 20-30% TLP plus Cryptograms. Charcoal is again variable with peaks at 99.1 and 101.8cm of up to 30% TLP plus Charcoal.

lpaz WB2b, 80-98.6cm, *Sphagnum-Pinus sylvestris-Calluna vulgaris-Betula*

Pinus pollen increases to 50% TLP at 88.5cm but declines above this, concentration is also low below 88.5cm but increases above. Pine stomata are present in all levels below 86.5cm, but disappear above this. *Betula* pollen comprises 20% TLP at the base of the zone but declines to about 10% TLP above 92.5cm but concentration is less variable. *Quercus* percentage is 2-3% TLP below 86.5cm, but declines above; *Alnus* and *Ulmus* pollen show low percentages and decrease and increase respectively. *Corylus* pollen always totals less than 2% TLP and disappears at 88.5cm; *Myrica* almost vanishes between 90.5 and 86.5cm. *Corylus avellana* type is unchanged from lpaz WB2a, but *Salix* pollen becomes less consistent.

Calluna percentages increase from 15% TLP below 92.5cm to around 25% TLP above; concentration is also low below 86.5cm. *A. uva ursa*, *E. cinerea* and *E. tetralix* pollen is virtually absent from this zone. *Empetrum* and *Vaccinium* percentages show shallow troughs in the middle of the zone, varying from 2-5% and 3-6% TLP respectively. *Phyllodoce* and *Pyrola* type have slightly more consistent presence than in previous or subsequent zones.

Poaceae pollen is at 5% TLP for most of the zone, but declines to about 1% TLP at the top of the zone; Cyperaceae also declines and becomes more sporadic. *P. lanceolata* and *Filipendula* pollen is consistently present at around 1% TLP.

Sphagnum percentages are very high in the zone, up to 60% TLP plus Cryptograms at 94cm. Charcoal is less important in this zone than in any other, there are no large peaks and percentage is typically around 5% TLP plus Charcoal.

lpaz WB3, 12-80cm, *Calluna vulgaris-Vaccinium-Myrica gale-Pinus sylvestris*

Radiocarbon assay, 56.5-57.5cm, 980±35 years BP

Pinus pollen comprises less than 20% TLP for most of the zone, it exceeds 20% above 34.5cm but there are no pine stomata in any level. *Alnus* percentage does not exceed 3% TLP in this zone; *Betula* does not exceed 10% TLP. *Quercus, Ulmus, Corylus* and *Corylus avellana* type pollen is present throughout the zone at less than 1% TLP, but *Myrica* pollen is much more important, with peaks of up to 10% TLP at 66.5 and 42.5cm.

Calluna pollen always totals more than 20% TLP and the percentages of other heaths are also relatively high. *Vaccinium* comprises 5-10% TLP, *Empetrum* and *E. tetralix* are present in all levels at less than 5% and 2% TLP and Ericaceae undifferentiated comprise 10% TLP. *P. coerulea* and *Pyrola* type are present only in the first level of the zone.

Poaceae and Cyperaceae pollen is present in all levels at around 5% TLP and less than 4% TLP. *P. lanceolata* and *Filipendula* are present in most levels in this zone.

Sphagnum percentages have declined from the previous zone to around 5% TLP plus Cryptograms through most of the zone. Charcoal is rather more important, especially between 36.5 and 42.5cm where Charcoal reaches almost 35% TLP plus Charcoal.

5.3.2 Description of results from rarefaction analysis

Results of rarefaction analysis are shown in Figure 5.3. Values range from 39 (99.1cm) to 26.5 (109.8cm). Confidence intervals are relatively high, but nonetheless palynological richness shows long sections of directional change, especially from 108.5cm (the bottom of WB1b) to 99.1cm (the top of WB2a). Between 94.5 and 86.5cm, from 74.5cm to the surface and below 108.5cm palynological richness is more variable. There are two sections of shorter directional change (98.5 to 94.5cm and 86.5 to 64.5cm). Highest consistent values are in WB2a, but errors are also greater.

Table 5.3 White Bridge radiocarbon dates and calculated accumulation rates

Stratigraphic position	Date range ±2σ (cal years BP)	Midpoint (cal years BP)	Sedimentation rates calculated from surface		Sedimentation calculated from date above	
			Range of sedimentation rates	Mean rate of sedimentation	Range of sedimentation rates	Midpoint to midpoint
57-58 cm	990-1160	1075	20.2-17.2 cal yr cm^{-1}	18.7 cal yr cm^{-1}	20.2-17.2 cal yr cm^{-1}	18.7 cal yr cm^{-1}
113.5-114.5 cm	3490-3690	3590	32.6-30.9 cal yr cm^{-1}	31.5 cal yr cm^{-1}	47.8-41.2 cal yr cm^{-1}	44.5 cal yr cm^{-1}

5.4 Dating model and description of pollen influx

5.4.1 Dating model

Peat accumulation rates calculated from the two radiocarbon assays from White Bridge are shown in Table 5.3. The two assays give different accumulation rates. Assay WB2, from poorly consolidated sedge peat indicates a more rapid accumulation rate than assay WB1. Changes in accumulation rate are to be expected in a sequence, but assay WB1 also has a low LOI, making inclusion of reworked sediment, including old carbon, a possibility.

The assemblage of deteriorated pollen is not in agreement with input of re-worked sediment. Deteriorated pollen is relatively abundant at the very base of the

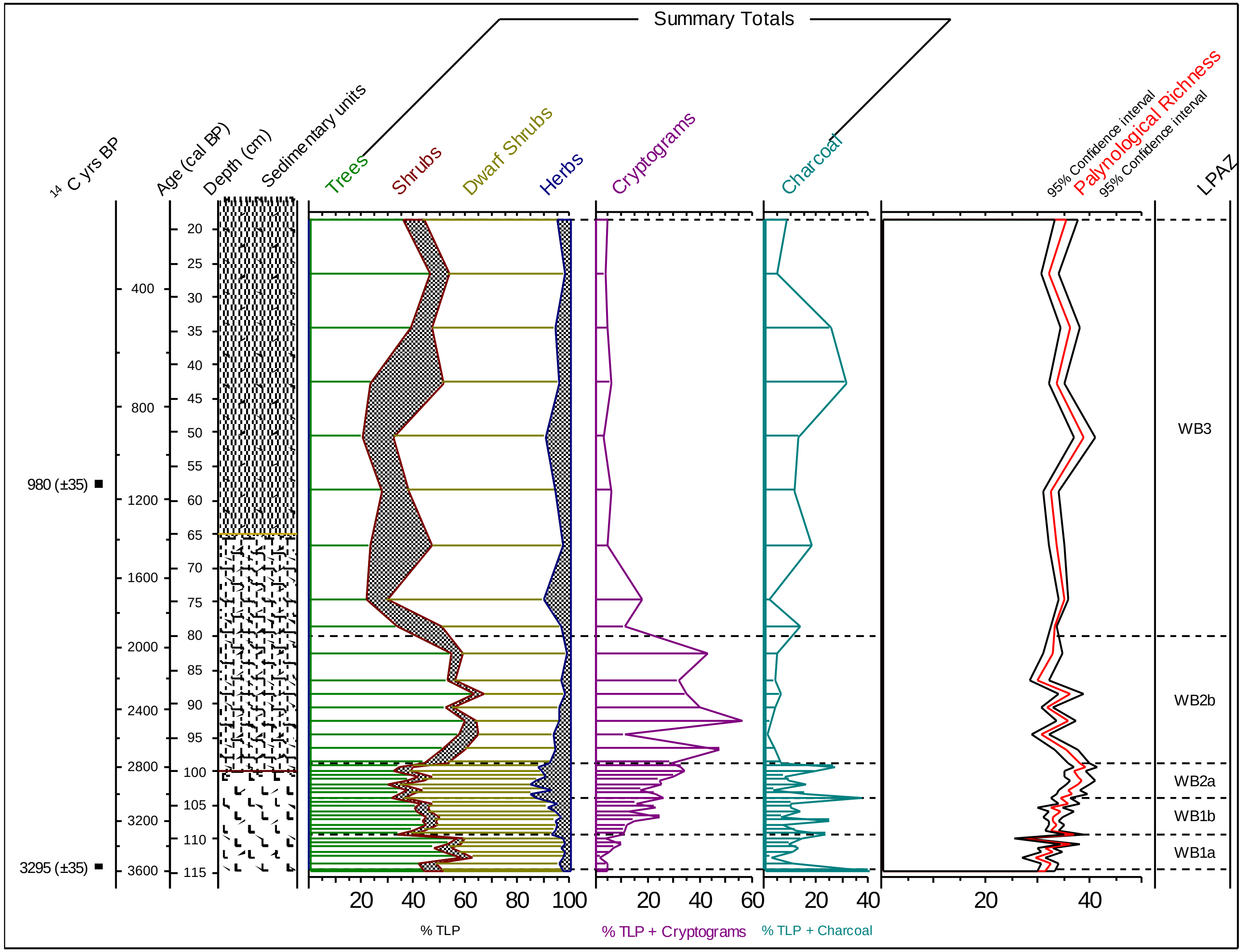


Figure 5.3 Results of White Bridge rarefaction analysis, with summary percentage pollen diagrams

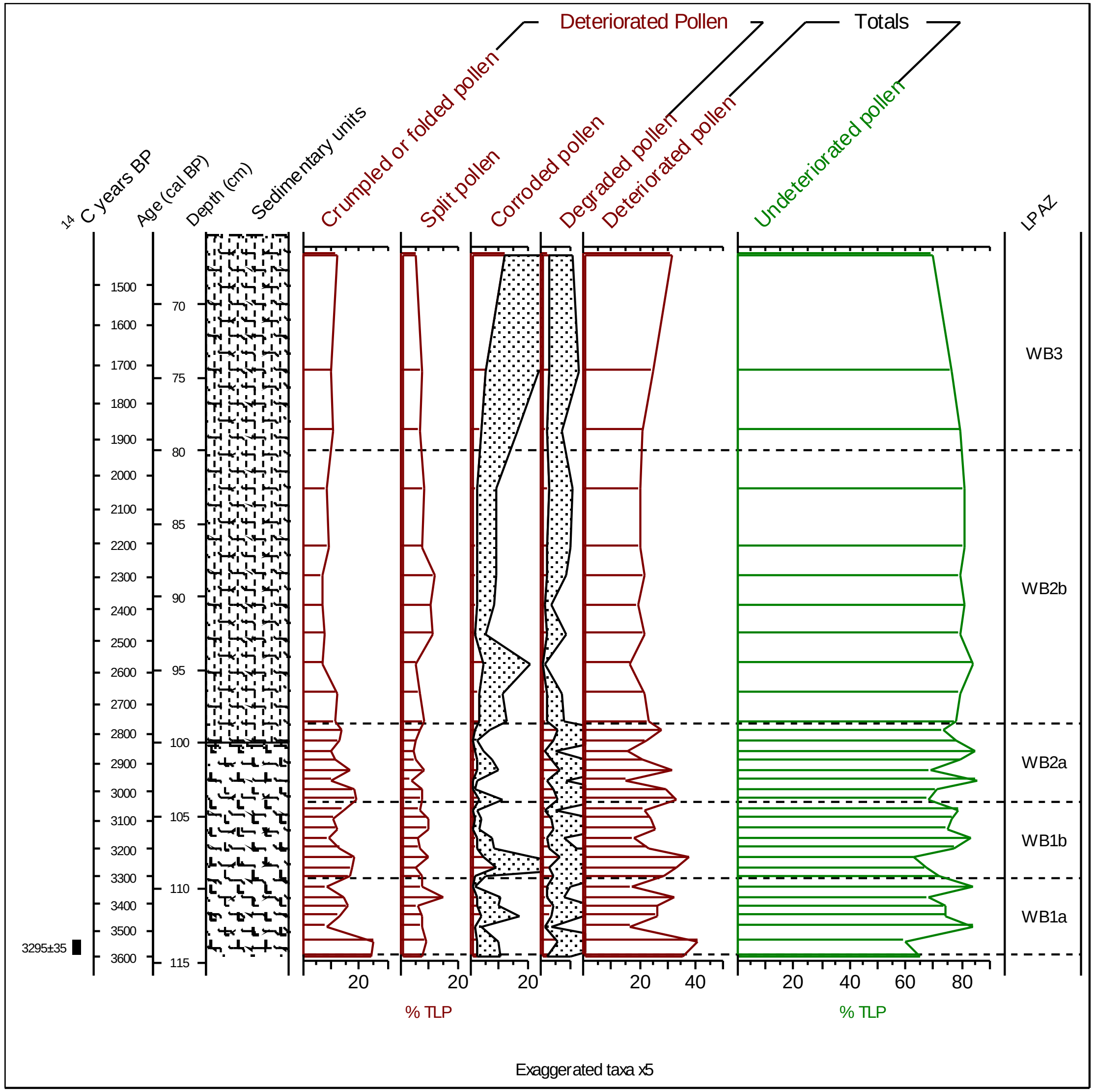


Figure 5.4 Deteriorated pollen between 66 and 114.5cm

sequence (Figure 5.4 and A.2a) but only slightly higher than elsewhere in the sequence.

Crumpled or folded pollen is the largest group within deteriorated pollen, likely to occur as a result of mechanical damage, whilst corroded and degraded grains are more likely to indicate re-working (Tipping 2000) and are not major components (Figure 5.4).

The position of the change in accumulation rate is unclear from the radiocarbon dates and definition of such change from only a few radiocarbon assays is difficult (Ashmore *et al.* 2004). The change in Troels-Smith designation at 100cm (Table 5.1, Figure 5.1) suggests an abrupt change in sedimentary environment and perhaps an abrupt change in the rate of accumulation. The peat becomes less obviously consolidated and there is an increase in identifiable plant material. Percent LOI increases from the base of the sequence but this increase is interrupted by a sustained decline in values from 106-100 cm. The final transition from low to relatively high LOI takes place between 100 and 96 cm, above the change in Troels Smith designation. Changes to light transmission are less supportive of an abrupt change in sediment regime, declining to a low point by 106cm, but then increasing and decreasing again between 106 and 94cm.

The main change in pollen defining the stratigraphy around 100cm is the increase in *Sphagnum*. Increases in *Sphagnum* are large, but start below, and continue above, 100cm. Most of the pollen taxa which occur consistently throughout the sequence show declining concentrations (Figures A.2b); such changes can help to define rates of change in sediment accumulation. Pollen concentration is as likely to reflect changes in vegetation as changes in sedimentation rate, but with so many gradual decreases, it seems probable that concentration is in agreement with a gradual change in sediment accumulation. Declines in individual taxa and total pollen concentration start from about 108cm rather than 100cm, so are not in agreement with a sudden change at 100cm.

The lack of corroborating evidence to define an abrupt change in sediment accumulation does not mean this does not occur, but the position of such a change cannot be firmly identified. A second order polynomial curve (Figure 5.5) provides a reasonable description of a gradual change in accumulation rate below about 60cm.

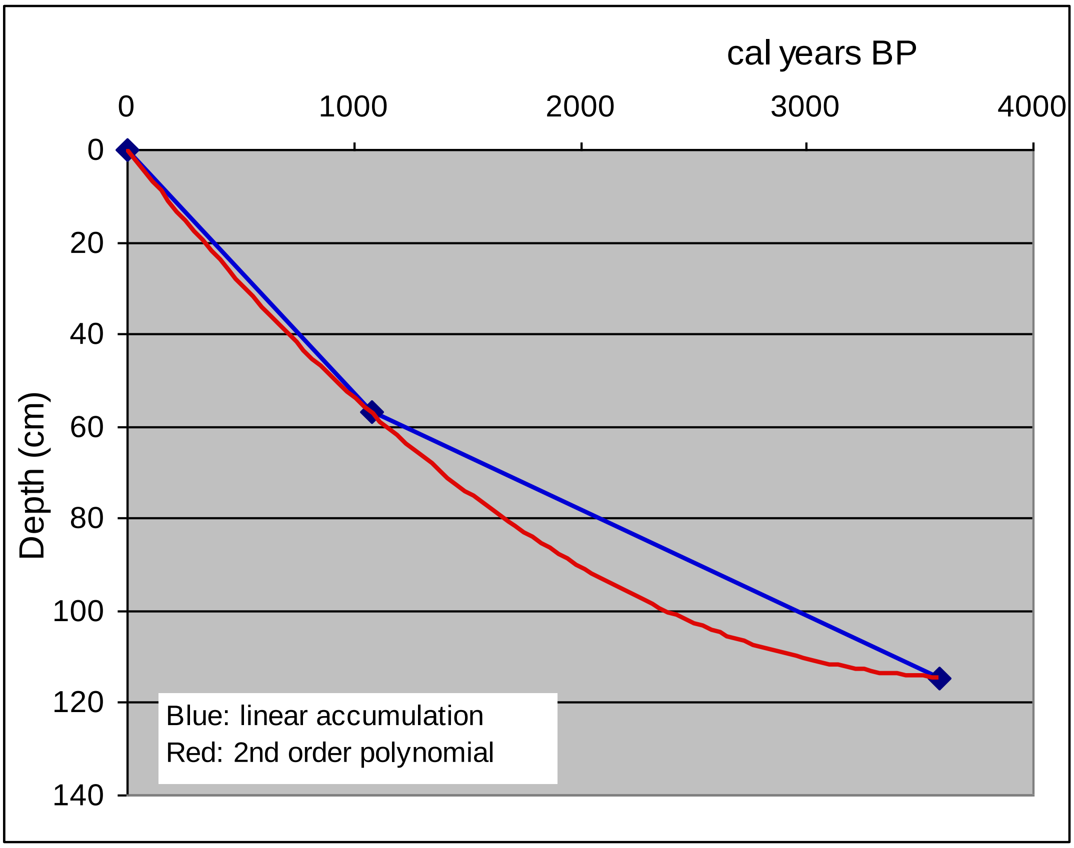


Figure 5.5 White Bridge age-depth model

The second order polynomial curve is used to calculate pollen influx for White Bridge (Section 5.4.2). Influx diagrams for selected taxa from White Bridge are presented in Figures A.2c. Local pollen assemblage zones are from percentage data.

5.4.2 Descriptions of pollen influx data

lpaz WB1a, 109.6-114.5cm, *c.* 3330-3590 cal BP

Calluna vulgaris-Pinus sylvestris

Pinus values are variable, between 2000 and 1000 grains cm^{-2} yr^{-1}. *Betula* influx declines from 400 at the base to 100 grains cm^{-2} yr^{-1} at the top of the zone; *Alnus* influx also declines, from 250 to 50 grains cm^{-2} yr^{-1} and other arboreal taxa have very low values and are only sporadically present. *Calluna* influx is between 500 and 750 grains cm^{-2} yr^{-1} but other heaths decline: *Empetrum* from 200 to 70 grains cm^{-2} yr^{-1}, *E. tetralix* from 200 to 50 grains cm^{-2} yr^{-1} and *Vaccinium* from 500 to 150 grains cm^{-2} yr^{-1}. Poaceae initially peaks at over 200 grains cm^{-2} yr^{-1} (*c*. 3530 cal BP) but drops to 50 grains cm^{-2} yr^{-1} by *c*. 3450 cal BP. *Sphagnum* influx is about 250 grains cm^{-2} yr^{-1} throughout.

lpaz WB1b, 104.4-109.6cm, *c.* 3050-3330 cal BP

***Pinus sylvestris-Calluna vulgaris-Betula-Sphagnum*-Poaceae**

Pinus influx decreases from 2000 grains cm^{-2} yr^{-1} to about 750 grains cm^{-2} yr^{-1} by *c*. 3130 cal BP. *Betula* and *Alnus* also decline from 600 to 100 and 450 to 50 grains cm^{-2} yr^{-1} respectively, by the top of the zone. *Quercus* and *Ulmus* have values of less than 20 grains cm^{-2} yr^{-1}. *Calluna* has no directional change but fluctuates between about 500 and 1000 grains cm^{-2} yr^{-1}. All other heaths and Poaceae decline from high values in this zone: *Empetrum* from 350 to 50, *E. tetralix* from 300 to 50, *Vaccinium* from 850 to 170 and Poaceae from 450 to 200 grains cm^{-2} yr^{-1}. *Sphagnum* is variable but increases from 500 to more than 1500 grains cm^{-2} yr^{-1}.

lpaz WB2a, 98.6-104.4cm, *c.* 2770-3050 cal BP

Pinus sylvestris*-*Sphagnum*-*Calluna vulgaris*-Poaceae-*Betula

Pinus values decline from about 750 grains cm^{-2} yr^{-1} at the base of the zone, to less than 500 grains cm^{-2} yr^{-1} by *c*. 2790 cal BP. *Betula* decreases from 300 to 200 grains cm^{-2} yr^{-1}, and *Alnus* from 100 to less than 50 grains cm^{-2} yr^{-1}, from the base to the top of the zone. *Ulmus* and *Quercus* have very low influxes (less than 10 grains cm^{-2} yr^{-1}) and show no directional change in this zone. *Calluna* and *Vaccinium* decrease from about 1000 to 200 and 250 to 150 grains cm^{-2} yr^{-1} respectively; *Empetrum* influx is low (about 50 grains cm^{-2} yr^{-1}) with no directional change, but *E. tetralix* declines. Poaceae influx declines from about 400 to 100 grains cm^{-2} yr^{-1}.

lpaz WB2b, 80-98.6cm, *c*. 1930-2770 cal BP

Pinus sylvestris*-*Sphagnum*-*Calluna vulgaris*-Poaceae-*Betula

Pinus influx increases from 500 to 1000 grains cm^{-2} yr^{-1}, by *c*. 2200 cal BP. Initially *Betula* influx declines slightly from about 200 grains cm^{-1} yr^{-1}, but recovers to about 300 grains cm^{-2} yr^{-1} after *c*. 2200 cal BP. *Alnus* influx is less than 50 grains cm^{-2} yr^{-1} and *Quercus* and *Ulmus* influx less than 20 grains cm^{-2} yr^{-1} for the whole zone. *Calluna* declines from 250 to 200 grains cm^{-2} yr^{-1} by *c*. 2660 cal BP, before recovering to more than 500 grains cm^{-2} yr^{-1} after *c*. 2200 cal BP. *Vaccinium* declines from 200 grains cm^{-2} yr^{-1} to less than 30 grains cm^{-2} yr^{-1} after *c*. 2260 cal BP. *Empetrum* values fluctuate around 50-100 grains cm^{-2} yr^{-1} with no directional change and *E. tetralix* almost disappears. Poaceae and Cyperaceae are low, less than 50 and 5 grains cm^{-2} yr^{-1} respectively. Apart from *c*. 2470 cal BP *Sphagnum* continues to increase, from about 750 to 1500 grains cm^{-2} yr^{-1}.

lpaz WB3, 12-80cm, *c.* 220-1930 cal BP

Calluna vulgaris-Vaccinium-Myrica gale-Pinus sylvestris

Pinus has influxes of less than 500 grains cm^{-2} yr^{-1} before *c.* 510 cal BP but increases to 1500 grains cm^{-2} yr^{-1} after this. *Betula* shows a similar pattern with increases from 200 to 400 grains cm^{-2} yr^{-1} and to 700 grains cm^{-2} yr^{-1} by the top of the zone. *Alnus* and *Ulmus* influx also increases after *c.* 510 cal BP, from 50 to 250 and 5 to 30 grains cm^{-2} yr^{-1} but *Quercus* increases from the base of the zone from 10 to 50 grains cm^{-2} yr^{-1}. *Calluna* influx increases from about 400 to 1200 grains cm^{-2} yr^{-1} before *c.* 700 cal BP, it then declines between *c.* 700 and 350 cal BP, but reaches 2500 grains cm^{-2} yr^{-1} at the top of the zone. Similarly *E. tetralix* increases from 10 to 100 grains cm^{-2} yr^{-1} from the base to the top of the zone. Excepting a single level (*c.* 350 cal BP), *Empetrum* and *Vaccinium* both increase 40 to 350 and 150 to 500 grains cm^{-2} yr^{-1}. Cyperaceae peaks at 100 grains cm^{-2} yr^{-1} at *c.* 910 cal BP. Poaceae increases from *c.* 50 to 300 grains cm^{-2} yr^{-1}. *Sphagnum* remains below 100 grains cm^{-2} yr^{-1} throughout the zone.

5.5 Interpretation of data from White Bridge

The modern landscape around White Bridge consists of three different landforms and substrates (Section 3.3.2), which are likely to have persisted throughout the history of sediment accumulation in the palaeochannel. The northern side of the valley is just over 200m from the core site. Arboreal taxa such as *Betula* growing there would contribute a large proportion of pollen to the core site. The northern terrace is within about 5m of the core site and today represents one type of environment favoured by *Pinus* (Carlisle and Brown 1968). The palaeochannel has probably always been wetter than the terrace. The area between the palaeochannel and the modern river represents an intermediary substrate in terms of both hydrology and sediment. Although around 50% of the arboreal pollen reaching the core site could have originated from up to 300m away (Section 2.3.4), non-arboreal pollen is likely to originate from much closer. Pollen from taxa with a small RSAP, including *Calluna, Empetrum, Vaccinium* and Poaceae, have an RSAP of 2m according to Bunting (2003). As the core site lies closer to the northern edge of the palaeochannel, pollen from taxa with a small RSAP is likely to correlate more closely with vegetation from the palaeochannel and the dry terrace, than from the more distal area south of the palaeochannel.

One facet of the interpretation of the pollen assemblage at White Bridge is the way in which it is possible to differentiate between vegetation from different substrates. The extent to which this differentiation is possible depends on the resolution of analyses, both temporal and spatial, with the close-interval sampling of the lowermost sediments approaching ecologically relevant timescales. The probable accumulation rates mean that at the base the number of years per sample is around 12-13, and the time between samples in the order of 30 years.

lpaz WB1a, 109.5-114.5cm, *c.* 3320-3590 cal BP

Pinus sylvestris-Calluna vulgaris-Vaccinium-Empetrum-Betula

Basin environment

Low LOI percentages at the base of the sequence indicate that the influence from flowing water is relatively important (Figure 5.1). The small particle sizes of the mineral sediment shows that the palaeochannel was no longer the main channel of the river. Low energy water flow could be overflow from the main channel or run-off from the terrace.

Polypodium vulgare is present in five of the seven samples in this zone (Figure A.2a) and while it is not common, its preference for rocks, walls and banks (Stace 1991) suggests that these environments were available in the channel initially. It occurs in only two levels above this zone, suggesting that initially the banks of the palaeochannel provided a shaded less open substrate but that such substrates disappeared as the channel filled. The channel bed included cobbles and boulders, which are apparent now as changes in peat depth in the palaeochannel (Figure 3.9). High light transmission values indicate a wet surface, which in view of the likely rocky substrate, may reflect the influence of ground water or persistent low water flows. It is not possible to differentiate between these two sources.

Fire

There is good evidence that fire is important in the development of the landscape during WB1a, and that fire affected the local area. Charcoal percentages have an abrupt decline from the initial single level peak at the base of the zone, but from *c.* 3530 cal BP to the top of the zone, charcoal percentages steadily increase (Figure A.2a). The ratio of large to small particles (Figure A.2d) also increases, suggesting more proximal fire (Clark and Royall 1995). There are also very large particles (long axis greater than 150μm) at *c.* 3590 and 3440 cal years BP and a particle of 140μm at *c.* 3480 cal years BP (Table 5.4), possibly representing fire within 10 and 100m of the site (Clark 1988, Peters and Higuera 2005).

Table 5.4 Large charcoal particles found within WB1a

Stratigraphic level (cm)	Length of longest axis (μm)	Total number of micro-charcoal particles	Ratio of large to small particles
111.8	280	65	0.5
112.5	140	13	0.2
114.5	250	67	0.4

Vegetation

The initial percentage of *Pinus*, 30% TLP, suggests semi-open to open woodland (O'Sullivan 1974a, Shaw 2006), but percentages increase to 40-50% TLP, suggesting a closing canopy. Stomata indicate that *Pinus* was initially present locally, at *c*. 3590 cal BP and again at *c.* 3400 cal BP, but disappeared from the immediate surroundings between and after these dates. Pollen influx of 1000 to 2000 grains cm^{-2} year^{-1} (Figure A.2c) is less than Jensen *et al.*'s (2007) or Hattestrand *et al.*'s (2008) finding for dense pine woodland, but in excess of the influx found by Jensen *et al.* (2007) for mixed pine-birch woodland or open pine woodland (200-400 grains cm^{-2} year^{-1}). *Betula* and *Corylus* are recorded initially at low percentages (10% and 5% TLP), just high enough for local presence (Huntley and Birks 1983, Shaw 2006) and in agreement with a mixed pine-birch woodland. The decline in concentration of *Betula* (Figure A.2b) may indicate a decrease in presence or its local disappearance, in agreement with a varying canopy and the increasing importance of *Pinus*.

Heaths dominated the ground flora: *Calluna* with *Vaccinium*, *Empetrum* and *E. tetralix*. The heath field layer included Poaceae and Cyperaceae, but neither are very important within the assemblage. In this zone *Sphagnum* increases slightly, but does not become important in the assemblage.

Fire could improve conditions for regeneration of *Pinus* (Berglund *et al.* 2004), and also for the dominant dwarf shrub, *Calluna* (Gimingham, 1960). The response time of *Calluna* would be less than the temporal 'grain' of the analysis, but regeneration of *Pinus* takes place over longer timescales. Possible local fire events at *c.* 3590 and 3440 cal BP correlate with reduced *Pinus* pollen percentages which, together with the disappearance of stomata between *c.* 3530 and 3400 cal years BP could represent local disappearance and re-growth of *Pinus* following local fire. *Pinus* concentrations are equivocal in inference, with intermittent increases from the base but a decline above *c.* 3440 cal years BP.

Palynological richness increases slightly from the base of the zone to *c.* 3370 cal BP (Figure 5.3). Influences on palynological richness include increasing vegetation diversity and changes in canopy density. A closing canopy may exclude long distance pollen input, resulting in lower palynological richness, but not necessarily indicating declines in the local vegetation diversity. In this instance canopy closure is in conjunction with increasing palynological richness, suggesting an increase in the diversity of the local vegetation (vad Odgaard 1999). Fires could create or maintain differences in the local vegetation mosaic, e.g. canopy density, which are then reflected in palynological richness values.

The differing light tolerance of the heaths within the pollen assemblage allows two alternative vegetation reconstructions: (1) semi-open to open *Pinus* woodland with an understory of heaths and some grasses, including occasional trees directly over the mire surface, or (2) a mosaic of communities, with denser stands of *Pinus* occupying a smaller area, (e.g. the northern terrace) but with an open, intermittently flooding channel. Shade tolerant *Vaccinium* would be favoured under the canopy, but will also grow in open conditions (Ritchie 1965). *Calluna* and *Empetrum* struggle in anything but open conditions (Gimingham 1960; Bell and Tallis 1973). *E. tetralix* prefers open conditions, but can tolerate wet, nutrient poor conditions (Bannister 1966).

The steady increase of *Calluna* is a good indicator of more open conditions, but *Pinus* increases at the same time suggest a differentiated landscape, with a relatively localised stand of *Pinus* giving a denser canopy. The local presence of open loving *Empetrum* (consistently exceeding 2% TLP) throughout the zone is in agreement with a small, denser stand of *Pinus*. The decline of shade tolerant *Vaccinium* is also in agreement with a vegetation mosaic; the interruption to its percentage decline is coincident with the reappearance of *Pinus* stomata (*c.* 3440 cal BP).

However, the small RSAP for both *Empetrum* and *Vaccinium* (about 2m: Bunting 2003) and *Calluna* means that open conditions could be limited to the palaeochannel itself, with *Pinus* more dispersed around the local area. Despite producing poorly dispersed pollen *Vaccinium* is still relatively important in the pollen assemblage; its percentage increase at *c.*

3440 cal BP probably better reflects a localised increase in canopy density. However, the slight rise and generally high (declining) percentage could describe a series of small patches of *Vaccinium* underneath scattered trees. This alone may be enough to conclude that the average vegetation solution rather than a mosaic solution is more appropriate.

Though the northern terrace would represent a 'favoured site' for *Pinus* and it is unlikely that the palaeochannel provided a good substrate for *Pinus*, the available pollen data does not allow a firm conclusion as to the location of *Pinus* in the landscape. There is no evidence to suggest that *Pinus* was excluded from the wider valley and *Betula* could have grown on the wetter area south of the palaeochannel, giving a semi-open pine-birch woodland of variable density with a mainly dwarf shrub field layer.

lpaz WB1b, 104.1-109.5cm, *c.* 3040-3320 cal BP

Pinus sylvestris-Calluna vulgaris-Empetrum-Vaccinium-Sphagnum

Basin environment

Decreasing light transmission values indicate that the peat surface became relatively drier. Decreasing LOI suggests a continuing decline in the influence of the river. Increases in *Sphagnum* are in agreement with a transition to a hummock and pool mire rather than a damp rocky substrate; the increase in *Sphagnum* also suggests a decline in substrate available to be colonised by *Pinus.*

Fire

Fire is as important in the environment as in WB1a. As in WB1a there is variation in charcoal indicative of changes in incidence of fire. Larger particles reflect a greater likelihood of fire very close to the core site, and at the top of the zone there is almost macroscopic-sized charcoal present (Table 5.5). At the base of the zone (108.5cm) the increase in total charcoal is mainly as a result of an increase in larger particles (greater than 50μm). The ratio of large to small particles increases from 0.4 to 0.8 (lpaz WB1a) to over 1 before declining again in WB1b.

The largest charcoal particles indicate fires within 10-100m (Clark and Royal, 1989, Peters and Higuera 2005). Therefore it is likely that fire affected the very local area within this zone, although there is little correlation between incidence of large particles and an increased ratio of large to small particles. There is such a correlation at 105.8cm, where a high particle count, a high ratio, and very large particles provides good evidence for a very local fire. This marks the start of a decline in *Pinus* pollen percentages.

Table 5.5 Large charcoal particles found within WB1b

Stratigraphic level (cm)	Length of longest axis (μm)	Total number of micro-charcoal particles	Ratio of large to small particles
105.1	250	69	0.6
105.8	250	83	0.5

Vegetation

At the base of the zone *Pinus* has abundance close to the threshold of local absence in many studies (approximately 20% TLP, Section 2.3). There are no stomata, in agreement with local disappearance, but *Pinus* concentration and influx have increased compared to the previous zone. The sudden fall in *Pinus* percentage and the rise in influx across the WB1a/1b boundary is contradictory, but may reflect year to year variation in pollen production that may become apparent as the sampling interval decreases. Subsequently *Pinus* percentages and influx trend in similar directions. *Pinus* percentages fluctuate between 25 and 35% TLP with peaks at *c.* 3060 and 3160 cal BP; influx is initially at values found by Jensen *et al.* (2007) within dense pine woodland. At the top of the zone, influx has declined to values found by Jensen *et al.* (2007) to indicate open woodland but by Seppa and Hicks (2006) to indicate background ‘noise’.

Correlation of declines in *Pinus* with fire events is sometimes possible, but not always with good evidence of local fire. The decline in *Pinus* pollen percentage across the WB1a and 1b boundary follows a series of small peaks in charcoal, and evidence for local fire toward the top of WB1b (*c*. 3080-3120 cal BP) is fairly strong. Although troughs in the *Pinus* pollen percentage both precede and follow this charcoal peak, *Pinus* influx and concentration decline steadily, in agreement with local disappearance of trees in response to a series of fires affecting the local area.

Influx of *Betula* and *Alnus* increases slightly. *Betula* percentage is again between the limits found by Huntley and Birks (1983) and Shaw (2006) to indicate local presence. *Alnus* is very unlikely to be present and reproducing locally. McVean (1955a) found that the maximum altitude at which *Alnus* forms viable embryos is 305m and that above 320m trees were entirely devoid of catkins. The main control on catkin production was found to be wind stress, making an open, relatively high valley such as Upper Glen Dee unlikely to have been a habitat that *Alnus* could colonise naturally. *Alnus* can grow higher than 320m, but the typical distance travelled by wind-dispersed seeds is 30-60m from the parent tree (McVean 1955a). Colonisation uphill, along a relatively shallow gradient such as Deeside is unlikely to have significantly altered the 10km distance between the modern altitudinal limit (Allanaquoich, NR1391, Figure 3.1) and White Bridge.

The increases in *Alnus* pollen are from extra-local or regional sources. The decline in *Pinus* leaves an open site, which favours input of long distance pollen; as between-trunk space increases, wind speed is increased keeping pollen airborne. Increases in relatively long distance pollen input also imply general fragmentation of the canopy in upper Deeside, between the *Alnus* source and the White Bridge site.

Palynological richness values are similar to WB1a, and show no directional change. If vegetation diversity was unchanged, palynological richness would be expected to rise during a phase of opening canopy. Similar values are probably not an indication that the canopy remains unchanged, but may show that vegetation in the wider landscape is less diverse than immediately surrounding the mire. It may be taken as (weak) evidence that *Pinus* was only sparsely present in the Dee valley near White Bridge.

The dwarf shrub assemblage is in agreement with either a scattered *Pinus* woodland or a discrete stand on the dry terrace. Percentages and concentrations of *Calluna* pollen increase, but there are small declines in pollen of *Vaccinium*, *Empetrum* and Ericaceae undifferentiated. The increase in *Empetrum* proportions across the boundary of WB1a and WB1b may be in response to a thinning *Pinus* canopy. *E. cinerea* has sporadic presence and *A. uva ursa* is more common in this zone than in others and influx of heath taxa excepting *Calluna* also decreases. *Calluna* and *Empetrum* prefer open conditions (Bell and Tallis 1973); *Calluna* thrives only when light levels exceed 40% of open conditions (Gimingham 1960). *E. cinerea* prefers well-drained acidic mineral sites with little humus accumulation and is able to tolerate relatively low light conditions (Bannister 1965). According to Bannister (1965) *E. cinerea* ‘occurs with 40% constancy in the *Pinetum-Hylocomieto-Vaccinietum-Myrtillosum* of McVean and Ratcliffe (1962). *Vaccinium* tolerates lower light conditions, and *A. uva ursa*, though a moorland or mountain species according to Stace (1991), is also a rare associate of *Pinus* woodland (Rodwell 1991).

Changes to the relative importance within the Ericales show *Calluna* to become more important at the expense of other dwarf shrubs. *Calluna* regenerates rapidly following fire, while *Vaccinium* and *Empetrum* can regenerate rapidly following low intensity fires, but struggle to recover from rhizome destroying fires (Ritchie 1956, Bell and Tallis 1973). Regeneration of *Vaccinium* and *Empetrum* is likely to be overwhelmed by *Calluna* if fire repeatedly affects the vegetation. The increases in charcoal might indicate human activity.

The increases of Poaceae to just over 5% TLP are small but are in agreement with an opening canopy. Increased fire in the landscape may also favour Poaceae. The relative pollen production of Poaceae is low, (Brostrom *et al*. 2004) and RSAP is 2m or less (Bunting *et al.* 2003), making even small increases in pollen likely to indicate increased abundance in the local vegetation (Mazier *et al.* (2006). The first appearance of *P. lanceolata,* regarded by Mazier *et al.* (2006) as an indicator of regional (human) disturbance, is at low percentages. Pollen productivity of *P. lanceolata* is 9-12 times that of Poaceae (Brostrom *et al.* 2004) and is 'characterised by long distance transport' in many studies according to Mazier *et al.* (2006) and Tinner *et al.* (2007). In view of these characteristics the relatively low percentages of *P. lanceolata* are in better agreement with extra-local presence. The increases in Poaceae, *P. lanceolata* and the single appearance of *Artemisia* (associated with rough or waste ground, [Stace 1991]), could indicate human activity in the valley.

The disparities between *Pinus* percentage, concentration and influx, the varied ecological preferences of the taxa in the field layer and the slight increases in palynological richness provide evidence in support of an increasingly differentiated landscape. Active human presence in the valley might have restricted the locations available to *Pinus* regeneration.

lpaz WB2a, 98.8-104.1cm, *c*. 2770-3040 cal BP

Pinus sylvestris-Sphagnum-Calluna vulgaris-Poaceae-*Betula*

Basin environment

The transition from an inorganic rich sediment to a *Sphagnum* mire continued in WB2a. *Sphagnum* increases from around 20% to 35% TLP plus Cryptograms, by *c.* 2760 cal BP. The base of the zone includes the last sustained LOI values of less than 80%, suggesting a decreased influence from flowing water. The increase in *Sphagnum* is likely to be indicative of, rather than the cause of, a change in water balance. Colorimetric light transmission still forms an inverse curve to LOI. Troels-Smith description is in agreement with the decline in inorganic material, in addition peat sediment becomes considerably less consolidated. The quantity of identifiable plant material increases, with sedge blades becoming discernable. Cyperaceae pollen is relatively unimportant but consistently at 2-3% TLP. There are no algal remains associated with open water identified in this zone, but the only two aquatic taxa identified from White Bridge are in this zone.

Fire

There is a high likelihood of very local fires within this zone, especially from *c.* 2820-2890 cal BP (99.8 and 101.1cm), where large particles of charcoal are present (Table 5.6). Charcoal counts are relatively high throughout the zone, making the high ratio of large to small particles a good indicator of more proximal fire compared to the zones above and below.

Table 5.6 Large charcoal particles found within WB2a

Stratigraphic level (cm)	Length of longest axis (μm)	Total number of micro-charcoal particles	Ratio of large to small particles
99.8	250	126	0.5
101.1	180 (2)	51	0.6

Vegetation

The semi-open to open woodland of WB1b fragments to form scattered pine-birch woodland; *Pinus* becomes less important but *Betula* may be more prevalent. After *c.* 2860 cal BP the canopy becomes increasingly open as heath dominated by *Calluna* replaces trees. Consistently high charcoal totals suggest that fire could have been affecting the local and extra-local vegetation throughout this zone. Human activity may be implicated in the emergence and maintenance of this vegetation assemblage.

Pinus percentages fluctuate between 20 and 30% TLP; open woodland to scattered trees according to O'Sullivan (1974a) and Shaw (2006). *Pinus* influx declines from about 700 to 400 grains cm^{-2} yr^{-1}, within estimates by Jensen *et al.* (2007) for open pine woodland. After increasing slightly (*c.* 2860 cal BP) influx falls to around 300 grains cm^{-2} yr^{-1}, in the middle of Jensen *et al.*'s (2007) values for open coastal pine woodland but well below the value associated with background 'noise' by Seppa and Hicks (2006). Low *Pinus* percentages at *c.* 2820 cal BP correlate with evidence for local fire, but precede similar evidence at *c.* 2890 cal BP. There is a single level with stomata (*c.* 2860 cal BP) preceding evidence for a local fire.

The increase in *Betula* (8-13% TLP) makes local presence more likely (Huntley and Birks 1983, Shaw 2006), especially after *c.* 2890 cal BP. Influx and concentration stop declining after this time. *Betula* may be replacing *Pinus*, but the combined influx of *Betula* and *Pinus* exceeds Jensen *et al.*'s (2007) estimates of 200-400 grains cm^{-2} yr $^{-1}$ for pine-birch woodland. Trees could be less common locally; *Pinus*, for example, may disappear from the dry terrace and be restricted to the valley sides. There are no important changes in other arboreal taxa and *Corylus* and *Corylus avellana* type also remain at similar values. *Salix* pollen is slightly more consistent in this zone, perhaps also in response to increased incidence of fire.

Calluna percentages are erratic. Three peaks of about 30% TLP are separated by two dips (*c.* 2860 and 2960 cal BP) to 15 and 20% TLP. Fluctuations in *Calluna* are negatively correlated with *Pinus* percentage. *Empetrum* always exceeds Binney's (1997) threshold for local presence; small variations in *Empetrum* are positively correlated with *Pinus*. Oscillations in *Empetrum* may be indicative of local changes but the consistent presence of *Vaccinium* (around 10% TLP) suggests that if there are canopy changes, there is little variation in the local area. This provides corroboration for local absence of trees but does not explain the variation between *Empetrum* and *Calluna*. These correlations may illustrate competitive interactions between *Calluna* and *Empetrum*.

E. tetralix decreases slightly and *A. uva ursa* becomes more sporadic but *Phyllodoce* is present in the upper two levels of WB1b and is more common in WB2a. *Pyrola* type, previously absent, appears in 2 levels in this zone and *E. cinerea* is slightly more common. *Phyllodoce* is found between 680 and 840m today (Stace 1991) and was unlikely to be present locally in the past, presence in the pollen assemblage is likely to indicate long distance input, favouring open local conditions. *Pyrola* type pollen includes *Moneses uniflora*, a good indicator of *Pinus* woodland (Stace 1991) but a lowland plant (Grime *et al.* 2007). *Pyrola* spp., evergreen, perennial herbs, found in damp heaths up to 1130m OD (Grime *et al.* 2007), sometimes as an understory to *Calluna*, were more likely to be locally present. *E. cinerea*, if present locally, was likely to occupy the dry terrace and its slight increase relates to the disappearance of trees from the local area.

E. tetralix, common in bog communities, was likely to be locally present on the mire. Decreases in its percentage could be explained by drying of the mire surface, but increases in *Sphagnum* suggest that the mire got wetter. Increases in *Sphagnum* could be related to changing water balance, for example, during a period of reduced summer temperatures. Lower summer temperatures also affect flowering and fruit maturation of *E. tetralix* (Bannister 1966) and lower the altitudinal limit of *P. caerulea*, making it more palynologically visible. A more likely scenario involves the tendency of *Sphagnum* to reduce nutrient availability thereby affecting the growth of vascular plants (Malmer *et al.* 1994).

Poaceae has percentages of up to 10% TLP. Small fluctuations in the percentage of Poaceae give a negative correlation with *Pinus* in agreement with open grassy areas. Several taxa associated with disturbed ground (Asteraceae, *Artemisia*, Caryophyllaceae, Chenopodiaceae, *Cirsium* type, *P. lanceolata* and *Potentilla* type) are found mainly in this zone. Mazier *et al.* (2006) found that the simultaneous occurrence of Asteroideae and Chichoriodeae (Asteraceae according to Stace 1991), *Cirsium* type, *Galium* type, Ranunculaceae, *Stellaria* type (within Caryophyllaceae following Moore *et al.* 1991) and *Potentilla* type pollen is 'clearly associated with grazing on a local scale' (Mazier *et al.* 2006). The extent to which the presence of some of these taxa could still indicate local grazing is unclear. Definite presence of two of these (*Cirsium*, *Potentilla* type), taken together with the possibility of three others within palynological 'families' (Asteroideae and Chichoriodeae- Asteraceae; *Stellaria* type- Caryophyllaceae) together with increases in Poaceae may be sufficient to infer light or very local grazing.

Models comparing AP/NAP ratios tend to underestimate vegetation openness, (Brostrom *et al.* 2004, Sugita *et al.* 1999, Sugita 2007a, Soepboer and Lotter 2009), the high ratio in WB2a suggests that the canopy was widely fragmented. Steadily increasing palynological richness may mainly derive from increases in long distance inputs, as well as the increases in locally derived disturbance indicators. The difference in RSAP between arboreal and non-arboreal taxa means that NAP taxa may be responding to changes not well correlated with the arboreal pollen signal (Sugita 1994, Sugita *et al*. 1999). Arboreal pollen in this zone is mainly or wholly derived from and reflects changes in the extra-local area. The high percentage of *Calluna*, suggests its pollen may be derived, to some extent, from both local and extra-local sources. Other heath and herb pollen responds to changes on the mire surface and perhaps the dry terrace.

lpaz WB2b, 80.5-98.6cm, *c.* 1930-2770 cal BP

Sphagnum-Pinus sylvestris-Calluna vulgaris-Betula

Basin environment

The basin is now best described as a *Sphagnum* mire. *Sphagnum* percentages are approaching Huntley and Birks' (1983) estimate of the maximum for *Sphagnum* mire. LOI is in agreement with the dominance of *Sphagnum* and the diminished importance of inorganic input. There is a single level (*c.* 2780 cal BP) where LOI is less than 80%, in agreement with an isolated, low energy delivery of mineral material. Cyperaceae percentages decline slightly and presence becomes sporadic, perhaps in response to the dominance of *Sphagnum*. There are no identified algal palynomorphs associated with open water. Colorimetric light transmission is not in good agreement with increasing mire surface wetness, but the decreases in light transmission may reflect increases in humic acid from higher organic content.

Table 5.7 Large charcoal particles found within WB2b

Stratigraphic level (cm)	Length of longest axis (μm)	Total number of micro-charcoal particles	Ratio of large to small particles
98.5	360	34	0.3

Fire

Fire is not important in the local or extra-local catchment for most of the zone. There is a single level with large particles of charcoal (Table 5.7), total charcoal is already declining and after *c.* 2760 cal BP charcoal in the assemblage almost disappears. Any further inferences using the ratio of large to small particles are unwise after this point.

Vegetation

The rise in *Pinus* percentage from 30 to 50% TLP follows the last indication of local fire at *c.* 2760 cal BP. Concentration and influx begin to increase and stomata become consistently present after the decline in charcoal at *c.* 2760 cal BP. Influx peaks at over 1000 grains cm^{-2} yr^{-1}, open pine woodland according to Seppa and Hicks (2006), Jensen *et al.* (2007) and Hattestrand *et al.* (2008). *Betula* may have been present at the base of the zone and becomes more common after *c.* 2660 cal BP, as percentage exceeds 15% TLP. A percentage decline after *c.* 2470 cal BP is not reflected in influx, and *Betula* probably disappeared from the local area after *c.* 2380 cal BP. Stomata disappear after *c.* 2210 cal BP, but *Pinus* remained important in the local vegetation assemblage to the top of WB2b.

It is unlikely that other trees were present. *Ulmus* reaches only about 1% TLP and *Alnus*, though with higher percentages, was unlikely to be present due to altitudinal constraints (see WB1b Interpretation). *Quercus* pollen increases to about 2% TLP, high enough for local presence according to Huntley and Birks (1983) but not according to Shaw (2006), who suggests 10% TLP is necessary. Increases in *Quercus* percentage probably relate to westward movement of the *Quercus-Pinus* ecotone in lower Deeside.

Calluna, *Vaccinium* and *Empetrum* were all present locally. As in WB2a the relationship between these three taxa and arboreal pollen is complex. After *c.* 2470 cal BP, *Calluna* percentage increases and *Vaccinium* percentages decline slightly, where a closing canopy might be expected to lower the light intensity, favouring *Vaccinium* (Ritchie 1956). *Empetrum* percentage also declines after *c.* 2470 cal BP, though it continues to exceed the 2% TLP threshold throughout the zone, indicating relatively open conditions.

E. tetralix pollen almost disappears from the assemblage. Continued rises in *Sphagnum* percentages are in agreement with an increased water balance; but this provides a mechanism for a decline in *E. tetralix* only if it is a result of declining summer temperature (Bannister 1966). *E. cinerea* does disappear from the assemblage. Though *E. cinerea* is better adapted to lower light conditions than *Calluna* (Bannister 1965), often forming an understory beneath *Calluna*, it is a poor competitor under wetter conditions (Bannister 1965). A decline in temperature would continue to explain the greater presence of *Phyllodoce*. Increases of *Pyrola* type, including either *Pyrola* spp. or *Moneses uniflora* seem more likely to reflect the reappearance of *Pinus* in the local area.

Poaceae declines gradually from 5% to 1% TLP. The start of the decline, *c.* 2760 cal BP, is coincident with the near disappearance of charcoal. Taxa associated with local human impact by Mazier *et al.* (2006) are largely absent, though *P. lanceolata* remains, indicating human activity in the regional area. The pattern of recovery in *Pinus* pollen values and reappearance of *Pinus* stomata may be the best indication that human activity decreased from *c.* 2760 cal BP. Recolonisation of the valley by *Pinus* may have commenced on the dry terrace and then spread further. Increasingly erratic palynological richness probably reflects ecotones within the local vegetation. Input of long distance pollen is interrupted as canopy closure causes variation of the pollen source area (vad Odgaard 1999).

lpaz WB3, 18.5-80cm, *c.* 220-1930 cal BP

Calluna vulgaris-Vaccinium-Myrica gale-Cyperaceae

Basin environment

Sphagnum diminishes in importance at the base of the zone, and remains less important. Increases in Cyperaceae and *Myrica* are large enough to suggest drying of the

Sphagnum dominated mire. Percentage LOI is again indicative of greater influence from surface flow, perhaps with intermittent flooding from the main channel. Decreases in LOI to about 40% do not correlate with changes in transmission. It is likely that changes in mire surface wetness relate as much to ground water as to runoff.

Fire

Fire was widespread and important in the extra-local landscape, but probably didn’t affect the local area. Charcoal counts increase from the very low numbers in WB2b. They remain high until the top of the zone but there are no charcoal particles larger than 150μm. The ratio of large to small particles increases above *c.* 700 cal BP but this occurs as charcoal totals decline. It is unwise to infer more proximal fire from this change.

Vegetation

Calluna with *Vaccinium*, *Empetrum* and *E. tetralix* dominates local vegetation. There were some areas of grassland but woodland was fragmented, the absence of stomata indicating no growth of *Pinus* within the local area at any point within WB3. It is possible that from *c*. 220-600 cal BP *Pinus* was more abundant in the valley than today, and was perhaps present in the extra-local area. There are some indicators of human activity, *P. lanceolata* is sporadically present and there is a single *Hordeum* type grain.

Before *c*. 510 cal BP *Pinus* pollen comprises less than 20% TLP; increases in percentage, influx and concentration after this suggest an increase in *Pinus* abundance in the valley, but there are no stomata, so *Pinus* remains absent from the core site. Subsequent increases in *Pinus* percentage occur as charcoal declines in importance. *Pinus* influx is high enough to indicate open woodland according to Seppa and Hicks (2006) and Jensen *et al.* (2007) after *c.* 510 cal BP. Ward *et al.* (1987), investigating transects from woodland to

Calluna-Erica moorland, found *Pinus* percentages falling to 1-2% TLP within 100m of a woodland edge (section 2.3.5), suggesting that at White Bridge, *Pinus* could have been found within 100m. The finding by Sugita *et al.* (1999) and Bunting *et al.* (2004) that 50% of an assemblage in an open situation may be derived from up to 1000m away is also in agreement with the presence of *Pinus* within the extra-local area. Brief declines in influx, concentration and percentage of *Betula* (*c*. 350 cal BP) suggest replacement by *Pinus*.

Many changes to the non-arboreal pollen assemblage are in agreement with a recovery in *Pinus* population. Concentration and influx of *Calluna* and *E. tetralix* decline between *c*. 900 and 350 cal BP. *Empetrum, Vaccinium, Myrica* and Poaceae concentrations and percentages decrease at *c*. 350 cal BP. One appearance of *Juniperus* (*c*. 910 cal BP) is in agreement with open conditions but a second appearance (*c*. 350 cal BP) occurs as *Pinus* increases.

Two measures of openness, e.g. *Pinus*/*Calluna* (McConnell and Legg 2003) and AP/NAP ratio do change in accordance with a closing canopy. However, *Empetrum* does not decrease below 2% TLP in WB3, and *Vaccinium*, which might benefit from a closing canopy, decreases slightly. These two taxa are good local indicators and are in agreement with *Pinus* remaining absent from the local area. Nonetheless, it is possible that *Pinus* was present, perhaps on the valley sides, closer than the 2-3km of extant trees. *Betula* is also likely to have been present in the valley. The waterfalls at the Chest of Dee are now good habitat for *Betula*, and were probably also were in the past; *Betula* could also have been present on the valley sides.

Initially *P. lanceolata* occurs at similar percentages as WB2b. Appearances are less consistent and the high pollen productivity and wide dispersal of *P. lanceolata* mean that the low percentages do not confirm local presence (Mazier *et al*. 2006, Tinner *et al*. 2007). Both percentage and consistency of *P. lanceolata* decline further after *c*. 1150 cal BP, somewhat before charcoal counts decline. The single *Hordeum* type cereal pollen grain at *c*. 910 cal BP could be derived from wild grass (Moore *et al.* 1991), but its stratigraphic position makes a cultivated origin possible. The lack of more cereal grains does not preclude cereal cropping in the area, but may reflect the 2m RSAP for Poaceae (Bunting 2003). In addition to the small decline at *c*. 350 cal BP, Poaceae tends to fluctuate from 3-5% TLP, about the same levels as the previous zone. The relatively low percentages reduce the chance of production of large wild pollen grains (Anderson 1979, Favre *et al.* 2006) but means that grassland remains an important component of the vegetation.

The combination of high charcoal percentages, *P. lanceolata, Cerealia* and Poaceae, are in agreement with human activity in the valley. *Hordeum* type pollen is consistent with agricultural activity based on barley growing and pastoralism. Likely positions for agricultural activity are on the alluvial fan to the south of the Chest of Dee, and near three townships within 1km of the White Bridge site. Decreases in *P. lanceolata* after *c*. 1150 cal BP suggest declining human influence; declines in charcoal after *c*. 700 cal BP are also in agreement with this.

6 Geldie Lodge: results and interpretation

6.1 Introduction

The results and the interpretation of the results from the Geldie Lodge core are presented here. Data including sediment descriptions and morphology, colorimetric data, percentage loss of mass on ignition (LOI) and radiocarbon assays are presented in Section 6.2. Descriptions of local pollen assemblage zones are presented in Section 6.3.1 and results of rarefaction analysis (palynological richness) are presented in Section 6.3.2. Dating models and pollen influx data are presented and described in Section 6.4. Interpretations of the Geldie Lodge data form the final section of this chapter (Section 6.5). All pollen diagrams are presented in Appendix A.3.

Table 6.1 Geldie Lodge sediment description

Depth (cm)	Colour	Description	Troels-Smith classification
0-4	Light brown	Moss.	Tb4
4-40	Mid brown	Peat, proportion of identifiable plant material increases upwards	Dh2 Th1 Sh1 Sb$^+$
40-82	Dark brown-mid brown	Amorphous peat with some identifiable plant material	Th2 Sh2
82-91	Black	Amorphous peat, no identifiable plant material	Sh4 Th$^+$
91-106	Dark brown to black	Amorphous peat with some identifiable ligneous plant material surrounding large wood fragment.	Th1 Dl2 Sh1
106-122	Black	Amorphous peat, a little identifiable plant material.	Th1 Sh3
122-128	Dark brown to black	Amorphous peat with some ligneous plant material surrounding wood fragments.	Th1 Dl2 Sh1
128-143	Dark brown to black	Mostly amorphous peat with some identifiable ligneous material. Remaining clay decreases upwards.	Th1 Dl1 Sh2 Ag$^+$
143-148	Dark brown to black	Amorphous peat with clay and silt.	Dl1 Ag2 As1

6.2 Sediment description and morphology, colorimetric data, percentage loss of mass on ignition and radiocarbon assays

The sediment description is shown in Table 6.1. The majority of the sequence consists of amorphous peat with only small amounts of recognizable plant material, including two thin layers with wood fragments (122-128cm and 91-106cm). Sediment below 143cm is rich in inorganic material and clay sized particles are still present in decreasing quantities to 128cm. Colour is mainly dark brown or black, but lightens to mid-brown above about 60cm. Eijkelkamp surveys of the mire stratigraphy, (Section 3.3, Figure 6.1), revealed that this stratigraphy was typical of the mire around the core site.

Colorimetric data and percentage loss-of-mass-on-ignition (LOI) are presented in Figure 6.2. Sub-samples below 139cm are from a piston core sample; sub-samples between 39 and 139cm are from the same 1.0m long Russian core, and sub-samples above 39cm come from a separate core.

Percentage LOI shows that organic content below about 130cm is variable, falling to around 50% at 134-132,142 and 148cm. The sediment is almost uniformly highly organic above 130cm, though there are two levels above 130cm with significantly lower organic contents (72 and 88cm), LOI values are always in excess of 70%.

Percentage light transmission at the base of the sequence is relatively high. Values then decline to the lowest value in the sequence at 116cm. Light transmission values from 128 to 14cm are low, typically less than 40%. The lowest value (23% at 116cm) is in a shallow trough from 128 to 110cm. There are periods of significant directional change, trends of 10-15% up or down. Between 38-60, 78-100 and 110-116cm values trend upward; values decline from 22-38, 60-76 and 116-126cm.

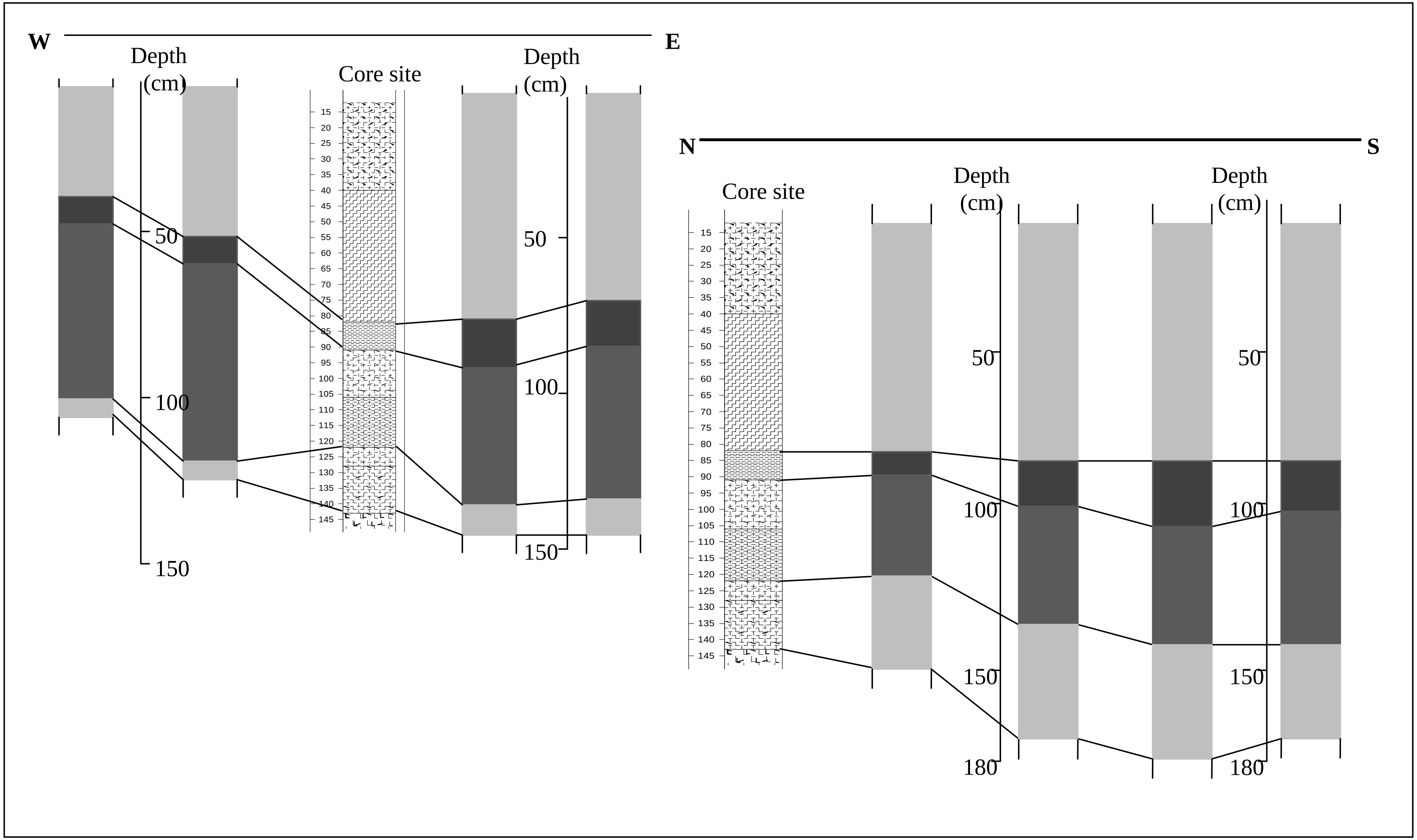


Figure 6.1. Peat cross sections Geldie Lodge. The depth and thickness of heavily humified sections are shown (darker colours) in east-west and north-south cross sections centred on the core site (Troels-Smith symbology). Columns are at 2m intervals on both transects.

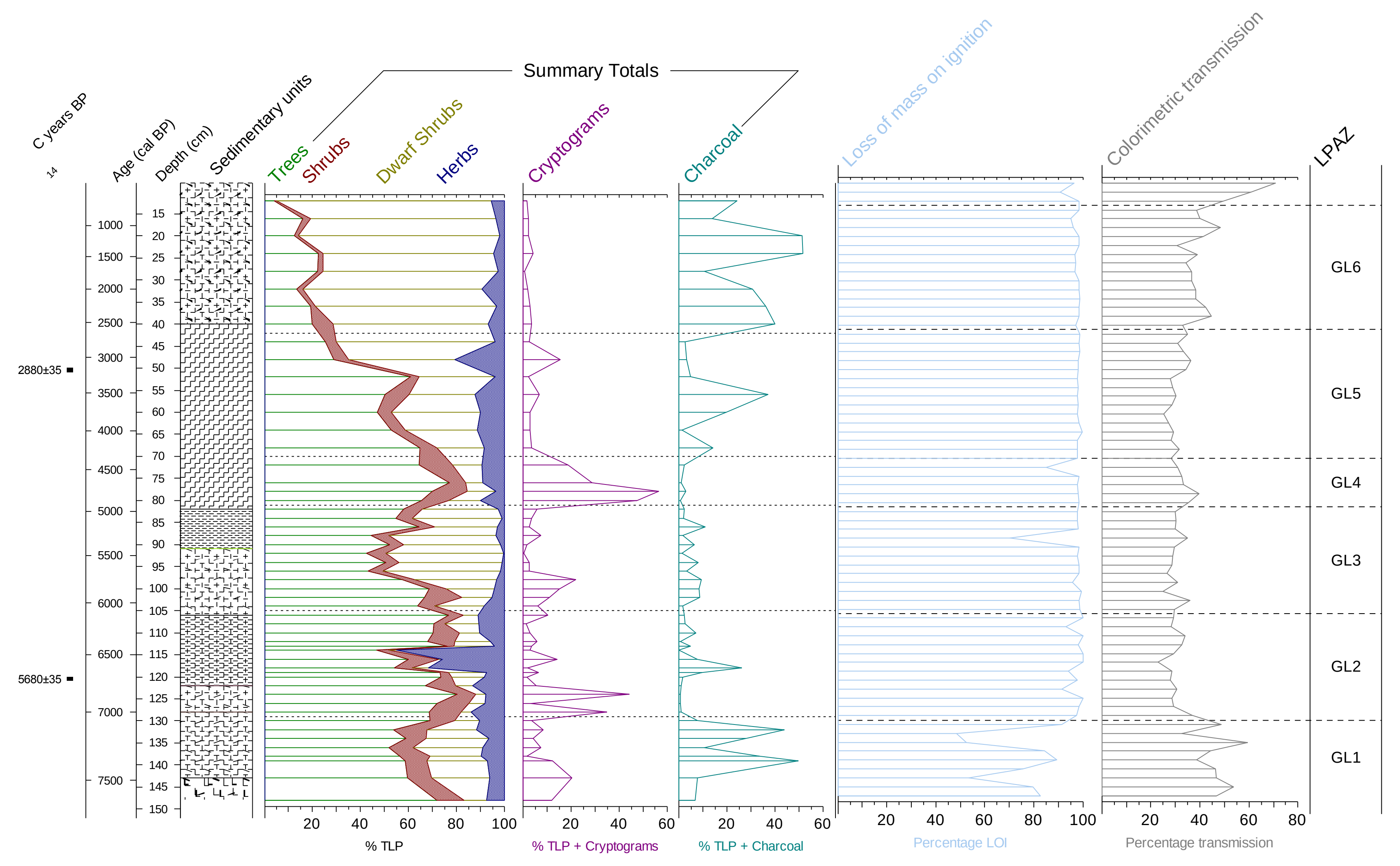


Figure 6.2 Geldie Lodge percentage loss of mass on ignition and percentage colorimetric transmission, with summary percentage pollen diagrams

Table 6.2 Results of radiocarbon assays for Geldie Lodge.

			Radiocarbon age	Loss of mass on ignition	$\delta^{13}C_{PDB}$	Calibrated age ±2σ using OxCal 3.1	
Laboratory code	Sample code	Depth (cm)	years BP ±1σ	% LOI	‰ ±0.1	Range, cal years BP	Midpoint (cal years BP)
GU-17252	GL3	50-51	2880±35	97	-23.6	3210-2970	3090
GU-17253	GL2	120-121	5680±35	92-98	-27.5	6620-6440	6530
GU-17254	GL1	140-145	5540±35	53-83	-26.2	6460-6330	6395

There are three radiocarbon assays available for Geldie Lodge, these are presented in Table 6.2. GL1 is taken from the piston core; GL2 and 3 are taken from the same, separate core. Assay GL1 (140-145cm) has a younger radiocarbon age than GL2 (120-121cm). There is a small overlap in the calibrated age range.

6.3 Descriptions of pollen assemblage zones and rarefaction analysis

6.3.1 Description of pollen assemblage zones

The Geldie Lodge sequence is divided into six local pollen assemblage zones (lpaz), GL1-6, marking major and minor changes in the pollen stratigraphy interpreted from stratified cluster analysis implemented via CONISS (Grimm 1987). Descriptions of lpaz are presented below. Diagrams showing percentage and concentration data are presented in Appendix A.

lpaz GL1, 129-148cm, *Pinus sylvestris-Betula-Calluna vulgaris*-Poaceae

Initially *Pinus* pollen comprises just under 50% TLP but declines to 30% TLP (140cm) before increasing to around 40% TLP at the top of the zone. Pine stomata are present from 144cm, disappear and reappear again after 138cm. *Betula* starts at 20%

TLP, declines to about 10% TLP (138-134cm) before rising to 20% TLP at the top of the zone. *Alnus*, *Quercus* and *Ulmus* pollen are present consistently throughout the zone at low percentages, 2-3%, 1-2% and 3-4% TLP respectively.

Corylus and *Myrica* are present at low percentages (less than 5% TLP) throughout the zone; *Corylus* increases slightly from the bottom of the zone to the top but *Myrica* shows no directional change. *Corylus avellana* type is consistently at 7-8% TLP throughout the zone. First appearance of *Salix* is at 144cm; it is present through much of the upper part of the zone excepting 134 and 136cm.

Calluna pollen increases steadily from 5% to 20% TLP from the base of the zone to 134cm, but dramatically declines to around 5% TLP at the top of the zone; Ericaceae undifferentiated is similar to *Calluna*. *Empetrum* and *Vaccinium* both show a small peak at 134cm but otherwise fluctuate around 1.5 and 3.5% TLP respectively.

The Poaceae curve rises gradually through the zone, from a low of less than 5% to around 10% TLP. Cyperaceae has a first appearance at 138cm and is present consistently above, rising slightly at the top of the zone to about 2% TLP. *Scabiosa* has a continuous curve in GL1 and includes two minor peaks at 148cm and 136cm. *Filipendula*, *Potentilla* type are sporadically present at around 1-2% TLP. Other taxa with occasional or sporadic appearance include Asteraceae (132, 134, 136 and 144cm) and Chenopodiaceae (132, 136 and 144cm).

Sphagnum declines above 144cm from 10-20 to 5-10% TLP plus Cryptograms. The charcoal curves rises dramatically and remains high to the top of the zone. The Charcoal curve shows the inverse to *Sphagnum*, increasing from 5-10%, with two peaks of up to 50% TLP plus Charcoal. The peaks are biased toward particles of less than 50μm.

lpaz GL2, 105-129cm, *Pinus sylvestris*-Poaceae-*Sphagnum*-*Betula*

Radiocarbon assay, 120-121cm, 5680±35 years BP

Pinus comprises more than 40% TLP at the base of the zone, but declines to about 30% TLP between 114 and 118cm; there is a similar pattern in the *Pinus* concentration curve. Pine stomata are also present in GL2. *Betula* trends down (from about 20% to 15% TLP) from the bottom to the top of the zone. Initially *Alnus* percentages are low (1-2% TLP) but increase to around 5% TLP above 120cm. *Quercus* and *Ulmus* are present at slightly higher percentages compared to GL1, both increase slightly from the bottom to the top of the zone.

Corylus percentages are similar to GL1 and *Corylus avellana* type again follows the *Corylus* curve. *Myrica* is present at slightly decreased percentages compared to GL1, except for a very small peak at 112cm (about 6% TLP). *Salix* is present from 106-110cm and 119 and 122cm.

The *Calluna* percentage fluctuates between 10% TLP (120cm) and less than 1% TLP (114-116cm); Ericaceae undifferentiated is also low and fluctuating. *Vaccinium* and *Empetrum* percentages are about 2% and 1% TLP; neither shows directional change. *Pyrola* type is present in 5 levels (112, 113, 118, 119 and 126cm) at less than 1% TLP and *A. uva ursa at* 110, 112 and 124cm.

There is a very large peak of Poaceae from 114-118cm, with percentages of over 30% TLP; this peak also appears in the concentration curve. Above and below this Poaceae fluctuates at around 5-10% TLP. Cyperaceae has a small single level peak (5% TLP) at 116cm, but is otherwise low (1-2% TLP) or absent (112, 118 and 126cm). *Filipendula* is absent from two levels (110 and 113cm) and is less than 1% TLP where present; *Potentilla* type is present at similar percentages to *Filipendula* but absent from only one level (126cm). There are *Hordeum* type cereal grains, (112, 113, 118, 119, 126 and 128cm) and Asteraceae and Rosaceae undifferentiated have a presence in 3 levels each: 116, 122 and 128cm and 108, 118 and 126cm respectively.

Two peaks of *Sphagnum*, 35 and 40% TLP plus Cryptograms (124 and 128cm) are separated by a low percentage at 126cm. Neither peak has *Tilletia* present but at 113 and 122cm there are lower counts of *Sphagnum* with *Tilletia*. *Polypodium* is present at 106, 108, 110, 112, 113 and 119cm. There is a large Charcoal peak at 118cm, evenly distributed across all size categories. Charcoal is almost absent from other levels in this zone.

lpaz GL3, 81-105cm, *Pinus sylvestris-Betula-Sphagnum-Calluna vulgaris*

Biostratigraphic correlation, 96-98cm, regional *Ulmus* decline, 6343-6307 cal BP

Pinus percentages decline in this zone, from 50% at the base of the zone to about 25% TLP between 88 and 96cm, before recovering to around 40% TLP at the top of the zone; *Pinus* concentration also has a distinct trough in the middle of the zone. Pine stomata are absent during the decreases, but reappear as *Pinus* percentages and concentration increase. *Betula* remains at around the same percentages as GL2, 15-20% TLP. *Alnus* increases steadily in this zone, from about 5% to 10% TLP. *Quercus* declines from 3% TLP at the base of the zone, to about 1% TLP (88cm) before increasing again at the very top of the zone to 5% TLP. *Ulmus* abruptly disappears (5% TLP to absent) from the assemblage between 96 and 98cm, but reappears at reduced percentages from 90cm upwards. *Corylus*, *Corylus avellana* type and *Myrica* are present in all levels at similar percentages to previous zones. *Salix* is present in three levels (86, 104 and 102cm).

Calluna has a large peak in percentage (40% TLP) and concentration during the *Pinus* declines, *Empetrum* also has a peak (3-5% TLP) at these levels, but

Vaccinium percentages fluctuate between 5 and 10% TLP with no directional change. *Pyrola* type is present in all but one level (100cm) at less than 1% TLP.

Poaceae percentage is low (less than 4% TLP) throughout the zone, falling to zero at 84 and 92cm. Cyperaceae is present in all but two levels (118 and 126cm) but at very low percentages, typically less than 1% TLP; *Filipendula* is also present in most levels (except 82, 88, 92 and 94cm). The first appearance of *P. lanceolata* in the Geldie Lodge sequence is at 96cm, but it is not present elsewhere in this zone. *Scabiosa* is present in one level (86cm). *Cerealia* (*Hordeum* type) is present in three levels: 82, 96 and 100cm.

Sphagnum has an initial peak in the lower zone (20% TLP plus Cryptograms at 98cm) but declines to less than 10% TLP plus Cryptograms above 98cm; *Tilletia* is present at 84 and 90cm. *Polypodium* is present in 5 levels (82, 90, 92, 98 and 100cm) at low percentages (less than 1% of TLP plus Cryptograms). Charcoal fluctuates at low percentages (1-10% TLP plus Charcoal) with no directional trend.

lpaz GL4, 70-81cm, *Pinus sylvestris*-*Sphagnum*-Pine stomata-*Betula*

Pinus percentage is high (50% TLP) at 76cm but lower (30% TLP) at the base and top of the zone; *Pinus* concentration does not show such a clear trend, but pine stomata are consistently present throughout the zone. *Betula* is at around 20% TLP but rises slightly at the top of the zone. *Alnus* is slightly higher than the previous zone, at about 10% TLP and *Ulmus* also has a slight recovery, rising to 2-3% TLP. *Quercus* is at a column high of more than 5% TLP in all levels. *Corylus* increases in this zone, from 5 to 10% TLP, *Corylus avellana* type also increases but *Myrica* does not show a similar rise.

Calluna percentage shows a trough in the middle of the zone but *Empetrum* and *Vaccinium* (about 5% each), show no directional change. *A. uva ursa* has a single level presence at 76cm and *Pyrola* type is present at 72cm and 80cm.

Poaceae increases slightly from the base to the top of the zone, to about 8% TLP. *Potentilla* type and *Filipendula* are absent from one level each (78 and 80 respectively) and Cyperaceae is absent from one level (78cm) but shows slightly higher percentages (about 5% TLP) than other zones. Chenopodiaceae is present at 76cm.

Sphagnum is at a column high of 45% TLP plus Cryptograms at the base of the zone but declines to 1-2% TLP plus Cryptograms toward the top of the zone. *Polypodium* and *Tilletia* are present at 72 and 80cm, *Pteridium aquilinum* is present at 72cm. Charcoal percentages are very low throughout the zone.

lpaz GL5. 42-70cm, *Calluna vulgaris-Pinus sylvestris-Betula*

Radiocarbon assay, 50-51cm, 2880 ±35 years BP

Pinus percentage is slightly lower for most of the zone (20-35% TLP) but drops above 56cm to around 10% TLP. *Pinus* concentration declines steadily throughout the zone but pine stomata are present at 48 and 64cm. *Alnus* and *Betula* are generally at the same percentages as GL4, but also decline above 50cm. *Quercus* gradually declines from the peak in the previous zone, but remains present; *Ulmus* declines and disappears above 52cm. *Corylus* varies around 1-4% TLP, but *Myrica* does not fluctuate and *Corylus avellana* type is also constant. *Salix* is present in two levels, 44 and 64cm.

The *Calluna* percentage increases at the base of the zone (10-20% TLP) but declines in the middle of the zone before increasing above 50cm to about 40% TLP.

Other heaths also increase: Ericaceae undifferentiated from about 5-15% TLP, *Empetrum* from less than 1% to about 3% TLP and *Vaccinium* from about 1 to 10% TLP. *E. tetralix* is present at 60 and 68cm and *A. uva ursa* at 52 and 68cm. *Pyrola* type is consistently present, but is always less than 1% TLP.

Poaceae is consistently at about 10% TLP before a decline above 56cm. *Filipendula* and *Potentilla* type are still present in all but one level each (44cm and 48cm respectively) at similar percentages to previous zones. *P. lanceolata* is now present in all levels except 56 and 68cm; its percentage stays below 1% TLP. *Scabiosa* reappears briefly at the base of the zone, before disappearing from the assemblage above 56cm. Asteraceae is present in a single level (48cm) at the top of the zone. *Cerealia* (*Hordeum* type) grains are found at 44 and 56cm.

Except for a single level peak at 48cm (about 15% TLP plus Cryptograms), *Sphagnum* is low (less than 5% TLP plus Cryptograms). *Sellaginella sellaginoides* is present at 52, 60 and 68cm and *Pteridium* at 48 and 52cm. There is a large peak of Charcoal (about 40% TLP plus Charcoal), which is biased toward larger particles (greater than 50µm) at 56cm.

lpaz GL6 12-42cm, *Calluna vulgaris-Vaccinium-Empetrum*

Pinus is below 10% TLP for the whole zone, concentration is low and pine stomata are absent. *Betula* also declines to between 5 and 10% TLP and *Alnus* is low, less than 5% TLP. *Quercus* is present at low percentages, (less than 1% TLP) and *Ulmus* is mostly absent from the zone with presence only at 24 and 32cm. *Corylus* is absent above 16cm; *Corylus avellana* type and *Myrica* are present throughout the zone at similar levels to the previous zone. *Salix* is present at 4 and 12cm.

Calluna is consistently present at 30% with peaks of up to 40% TLP; there is a similar rise in Ericaceae undifferentiated to as much as 30% TLP at 20cm. Both

Vaccinium and *Empetrum* also increase slightly through this zone from 10-15% TLP and 5-10% TLP respectively. *Pyrola* type increases slightly toward the top of the zone, showing a similar pattern to other heaths but only rising to 2-3% TLP. *E. tetralix* is present at 16, 20 and 28cm.

Poaceae is relatively low, 5% TLP or less throughout the zone. *P. lanceolata* is again consistently present, disappearing from only one level (24cm) but never reaching more than 1% TLP. *Filipendula* is absent from 16-32cm, Cyperaceae is present at 24, 32 and 40cm and *Potentilla* type is absent from 32cm and from 4-28cm. *Cerealia* (*Hordeum* type) is present at 24 and 32cm.

Sphagnum percentages are low in this zone, reaching 5% TLP plus Cryptograms at 24cm; *Tilletia* is also present at 24cm. Charcoal percentages are high throughout this zone, with two peaks in excess of 40% TLP plus Charcoal, separated by a single level dip to below 15% TLP plus Charcoal at 28cm; as with GL5 the increase is biased slightly toward larger particles (greater than 50μm). *Pteridium* and *Sellaginella sellaginoides* are both present at 32cm, *Sellaginella* appears again at 4cm.

6.3.2 Description of results from rarefaction analysis

Palynological richness is shown in Figure 6.3. Values range from 39.8 to 26.8 but there are few trends: most local pollen assemblage zones have almost as much internal variation as the whole sequence. Lpaz GL1 and GL2 have the most number of values in excess of 35, but lpaz GL2 also has three levels below 30, including the lowest value of the sequence. There are sections of the curve that show directional change, i.e. increase or decrease for four or more levels. From 16-28, 68-78, 86-92, 108-114 and 132-138cm richness increases; 40-52 and 126-132cm are sections of

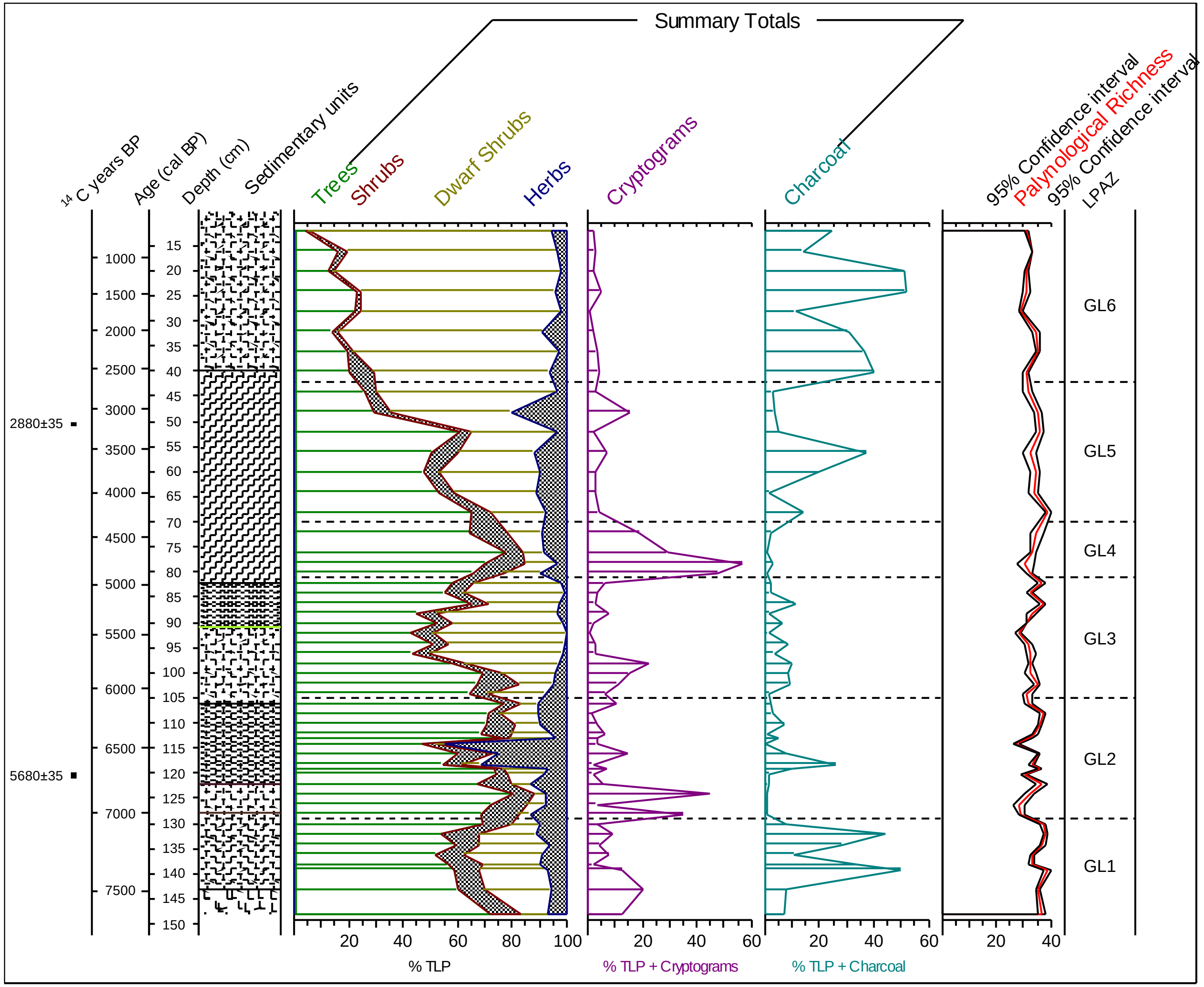


Figure 6.3 Results of Geldie Lodge rarefaction analysis, with summary percentage pollen diagrams.

decline. The longest period of decline, from 92-102cm is interrupted by a very slight increase at 96cm.

6.4 Dating model and description of pollen influx

6.4.1 Dating model

The Geldie Lodge dating model includes a date correlated with the regional decline in *Ulmus* (from *c*. 5281-6347 cal BP, 1066 cal years, Parker *et al.* 2002). Parker *et al*. (2002) describe the British *Ulmus* decline as a uniform phased event across the British Isles, with the onset within 36 years (between 6343 and 6307 cal BP at 1σ) and the end within 130 years (between 5290 and 5420 cal BP, at 1σ). *Ulmus* pollen is consistently present at Geldie Lodge below 98cm but disappears from 96cm (Figures A.3a), suggesting the onset of the regional decline to be between these stratigraphic levels.

Table 6.3 Geldie Lodge radiocarbon assays, correlated date and calculated accumulation rates

Stratigraphic position	Date range ±2σ (cal years BP)	Midpoint (cal years BP)	Sedimentation rates calculated from surface		Sedimentation calculated from date above	
			Range of sedimentation rates	Mean rate of sedimentation	Range of sedimentation rates	Midpoint to midpoint
50-51cm	2970-3210	3090	58.8-63.6 cal yr cm^{-1}	61.2 cal yr cm^{-1}	58.8-63.6 cal yr cm^{-1}	61.2 cal yr cm^{-1}
96-98cm (*Ulmus* decline)	6307-6343	6325	70.7-71.6 cal yr cm^{-1}	71.2 cal yr cm^{-1}	67.7-73.3 cal yr cm^{-1}	70.3 cal yr cm^{-1}
120-121cm	6440-6620	6530	46.1-52.1 cal yr cm^{-1}	49.1 cal yr cm^{-1}	4.4-12.5 cal yr cm^{-1}	8.5 cal yr cm^{-1}
140-145cm	6330-6660	6495	33.9-37.9 cal yr cm^{-1}	37.0 cal yr cm^{-1}	-15.3- 8.8 cal yr cm^{-1}	-3.25 cal yr cm^{-1}

The validity of the basal assay, GL1, from peat in contact with the underlying alluvial sediment, is thought more open to question than either of assays GL2 or GL3. It is possible that humic acids flowing down through the peat collected at and contaminated the basal peat (Hicks 2001). Roots penetrating from above could have introduced younger carbon or the sediment could be anomalously young as a result of lowered organic content (Walker and Lowe 1997, Ashmore *et al*. 2001). There is a peak in charcoal concentration at 119cm (just above assay GL2), but this is unlikely to affect the radiocarbon age at 120-121cm.

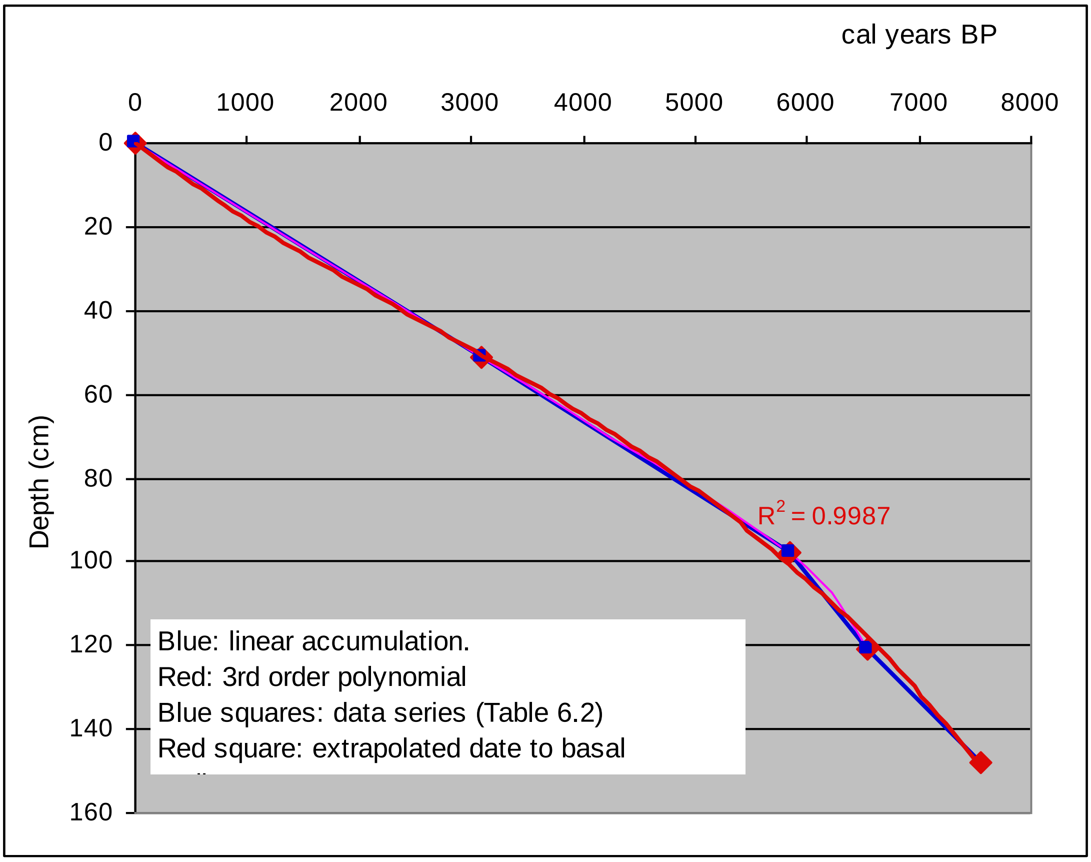


Figure 6.4 Geldie Lodge age-depth model

Calculated sediment accumulation rates from assays GL3, GL2 are similar, but the calculated accumulation rate from assay GL1 is considerably more rapid (Table 6.4). Calculated sedimentation rate based on the start and finish of the *Ulmus* decline at 96 and 84cm give accumulation rates that are slower still, but GL2 is closer than GL1 to the slower accumulation of the upper column. Figure 6.3 shows that accumulation combining assay GL3 and the *Ulmus* decline is close to linear, but decreases slightly between 84 and 96cm, assuming the modern surface is 0 cal BP.

Assay GL2 does not fit linearly, but a third order polynomial gives a reasonable fit. Extrapolation of the third order polynomial using *Tilia* (Grimm 1991) gives a basal date of *c*. 7550 cal BP. This extrapolation is used in the dating model adopted for Geldie Lodge, presented in Figure 6.4.

The basal extrapolation is younger than the radiocarbon date for inception of blanket peat at the nearest of Binney's (1997) sites, *c.* 8400 cal BP, at Carn a'Phris-Ghiubhais in Glean Einich. This is not necessarily significant and this basal date and dating model are used in interpretations; the 3rd order polynomial curve is used to calculate pollen influx. Influx diagrams for selected taxa from Geldie Lodge are presented in Figures A.3c. Local pollen assemblage zones are from percentage data.

6.4.2 Descriptions of pollen influx data

lpaz GL1, 129-148cm, *Pinus sylvestris-Betula-Calluna vulgaris*-Poaceae

***c*. 7030-7550 cal BP**

Pinus influx exceeds 1000 grains cm^{-2} yr^{-1} throughout the zone with peaks of 3000 grains cm^{-2} yr^{-1} at the base and top of the zone. *Betula* influx is in excess of 1000 grains cm^{-2} yr^{-1} at the base and top of the zone, but declines to about 250 grains cm^{-2} yr^{-1} at *c*. 7200 cal BP. Other arboreal taxa have values of 100 grains cm^{-2} yr^{-1} or less. *Calluna* influx is very low at the base, this increases after *c*. 7200 cal BP, from 200 to 900 grains cm^{-2} yr^{-1}; *Empetrum* also increases after this, from 40 to 100 grains cm^{-2} yr^{-1} but *Vaccinium* is relatively consistent at *circa* 100 grains cm^{-2} yr^{-1}. *Myrica* has a peak, 150 grains cm^{-2} yr^{-1}, at *c*. 7150 cal BP. Herbs have generally low influxes.

lpaz GL2, 105-129cm, *Pinus sylvestris-Sphagnum-Betula*-Poaceae

***c*. 6080-7030 cal BP**

Pinus influx is between 1000 and 2000 grains cm^{-2} yr^{-1} at the base of the zone. There are two single level peaks of *Pinus* in excess of 3500 grains cm^{-2} yr^{-1} at *c*. 6420 and 6780 cal BP; in between influx decreases to around 500 grains cm^{-2} yr^{-1}, but increases to over 1000 grains cm^{-2} yr^{-1} after *c*. 6420 cal BP. *Betula* and *Alnus* have a similar pattern, falling below 150 and 50 grains cm^{-2} yr^{-1} respectively, with high peaks, 1200 and 400 grains cm^{-2} yr^{-1}, at *c*. 6420 and 6780 cal BP. *Quercus* and *Ulmus* also have the same peaks and trough pattern at the same points. Heaths are all low throughout the zone and do not exhibit the same peaks as the arboreal taxa. Poaceae has the opposite pattern, peaking at 1000 to 2000 grains cm^{-2} yr^{-1} from *c*. 6460-6620 cal BP.

lpaz GL3, 81-105cm, *Pinus sylvestris-Betula-Sphagnum-Calluna vulgaris*

***c*. 4930-6080 cal BP**

Influxes for *Betula* and *Pinus* are variable. *Pinus* influx is as high as 4000 grains cm^{-2} yr^{-1} but falls below 1000 grains cm^{-2} yr^{-1}after *c*. 5150 cal BP. *Betula* influx is as high as 1750 grains cm^{-2} yr^{-1} and falls below 250 grains cm^{-2} yr^{-1} after *c*. 5150 cal BP. The *Ulmus* decline is apparent in influx, from over 400 grains cm^{-2} yr^{-1} at the base of the zone, to less than 40 grains cm^{-2} yr^{-1} *c*. 5750 cal BP. All Heaths have influx peaks between *c*. 5670-5770 cal BP with *Calluna*, *Empetrum* and *Vaccinium* showing peak influxes of 4500, 250 and 500 grains cm^{-2} yr^{-1} respectively. *Sphagnum* has a peak of up to 1000 grains cm^{-2} yr^{-1} between *c*. 5850 and 5750 cal BP.

lpaz GL4, 70-81cm, *Pinus sylvestris-Sphagnum*-Pine stomata-*Betula*

c. 4100-4930 cal BP

All arboreal pollen taxa have troughs within the zone. *Pinus* continues the decline from the top of the previous zone, dropping below 500 grains cm^{-2} yr^{-1} after *c*. 4770 cal BP. *Betula* drops below 250 grains cm^{-2} yr^{-1} before rising to 500 grains cm^{-2} yr^{-1} after *c*. 4500 cal BP. Other arboreal taxa decline: *Alnus* from 200-100, *Quercus* from 100-50 and *Ulmus* from 75-50 grains cm^{-2} yr^{-1} by *c*. 4660 cal BP, but all three taxa return to their initial values by the top of the zone. All heaths have low influxes, but all show declines similar to the arboreal taxa. Cyperaceae values are relatively high, with about 50-75 grains cm^{-2} yr^{-1} and no directional change, but Poaceae is very low throughout the zone. *Sphagnum* influx is high at the base of the zone, 1500 grains cm^{-2} yr^{-1}, but drops to 500 gains cm^{-2} yr^{-1} after *c*. 4770 cal BP.

lpaz GL5, 45-70cm, *Calluna vulgaris-Pinus sylvestris-Betula*

c. 2620-4100 cal BP

At the base of the zone *Pinus* influx is around 1000 grains cm^{-2} yr^{-1} but declines to around 200 grains cm^{-2} yr^{-1} by *c*. 2880 cal BP. Influx values for *Betula*, *Alnus*, *Quercus* and *Ulmus* also decline: from 500-250, 200-50, 100-20 and 75-10 grains cm^{-2} yr^{-1} respectively. *Calluna* and *Vaccinium* increase: *Vaccinium* from 50 to 250 grains cm^{-2} yr^{-1} and *Calluna* from 500 to 1000 grains cm^{-2} yr^{-1}. Poaceae influx increases slightly to around 250 grains cm^{-2} yr^{-1}.

lpaz GL6, 12-42cm, *Calluna vulgaris-Vaccinium-Empetrum*

***c*. 600-2620 cal BP**

Pinus influx is less than 200 grains cm^{-2} yr^{-1} throughout the zone. *Betula* influx is similar to the top of the previous zone, about 250 grains cm^{-2} yr^{-1}. Other arboreal taxa are typically less than 50 grains cm^{-2} yr^{-1}. All heath taxa are increased from the previous zone. *Calluna* is dominant, with two peaks of over 1000 grains cm^{-2} yr^{-1} (*c*. 1170 and 2260 cal BP) but values are variable and decline slightly from the base to the top of the zone. *Vaccinium* and Ericaceae undifferentiated are relatively high, with influxes of around 200 grains cm^{-2} yr^{-1}; *Empetrum* values are slightly lower, around 100 grains cm^{-2} yr^{-1}. Poaceae has its lowest influxes in this zone, about 100 grains cm^{-2} yr^{-1} but *P. lanceolata* has its highest values in this zone, 35 grains cm^{-2} yr^{-1}.

6.5 Interpretation of data from Geldie Lodge

lpaz GL1, 129-145cm, *c*. 7030-7550 cal BP

***Pinus sylvestris-Betula-Calluna vulgaris*-Poaceae**

Basin environment

Relatively high mineral contents (Figure 6.2, Table 6.1) are in agreement with mixing of peat and underlying alluvial sediment. The poor dispersal of *Sphagnum* spores suggests that *Sphagnum* probably formed part of the *in situ* soil at peat inception. The relative positions of the core site, the alluvial fan of Allt Coire an t-Seilich, and the modern river (Section 3.3, Figure 3.3), at the time of peat inception suggest that influence from Allt Coire an t-Seilich was not important. Declining *Sphagnum* percentages and light transmission after *c*. 7370 cal BP probably show drying of the mire surface after peat initiation.

Fire

Charcoal percentages are high for most of GL1. Peaks of nearly 50% TLP plus charcoal at *c.* 7370 and 7140 cal BP show the importance of fire in the landscape around Geldie Lodge. Large particles of charcoal from 7270 to 7200 cal BP (134 and 136cm, Table 6.7) suggest fires within 10 to 100m of the sampling site (Clark 1988, Peters and Higuera 2005). A high ratio of large to small particles (Figure A.3d) and the relatively high percentage of charcoal (Figure A.3a) at *c.* 7340 cal BP (138cm) are in agreement with this interpretation.

Table 6.4 Large charcoal particles found within GL1

Stratigraphic level	Length of longest axis	Ratio of large to small particles	Total charcoal particles
134cm	250µm	0.7	200
136cm	300µm	0.8	61

Vegetation

Stomata presence shows *Pinus* to be locally present from the beginning of the zone. The relatively low percentages of *Pinus* (30-40% TLP) suggest semi-open woodland (O'Sullivan 1974a, Shaw 2006). Initially *Betula* was probably also present locally, with percentages exceeding Shaw's (2006) intercept of 13% TLP, but may have disappeared locally between *c.* 7000 and 7340 cal BP, as percentage falls to around 10% TLP. Combined influx of *Pinus* and *Betula* exceeds the influx found by Jensen *et al.* (2007) and Hattestrand *et al.* (2008) for mixed pine-birch woodland. *Pinus* was probably the more common taxon, with *Betula* exploiting gaps in a *Pinus* canopy or forming the tree-line.

The percentage, concentration and influx values for both *Pinus* and *Betula* decline as charcoal totals increase and evidence for local fire becomes stronger (*c.* 7340 cal BP). Both taxa recover after this; the tree canopy returned to a similar density as earlier in the zone. Local presence of *Corylus* was more likely after *c.* 7340 cal BP as values exceed 5% TLP. Values at 1-5% TLP ‘cannot be attributed to definite local presence’ according to Birks (1989, page 508). At this early stage of peat development it is likely that all three taxa were able to exploit mineral soils around the core site. It is not likely that changes to the course of Allt Coire an t-Seilich interfered with tree growth.

Quercus and *Ulmus* are close to values considered indicative of local presence. It is unlikely that these taxa, or *Alnus*, were present at this altitude. Though (managed) *Ulmus* is recorded as growing to 535m at Athol in east Perthshire, naturally growing saplings are not found above 300m (Grime *et al.* 2007), making natural colonisation at Geldie Lodge (510m) unlikely. *Quercus* is now limited to about 450m (Grime *et al.* 2007) and *Alnus* is not found above 320m (McVean 1955a). All three taxas’ altitudinal limits may have been higher in the past, but change would have had to have been considerable to allow local presence at Geldie Lodge. The late spring frosts typical of the Cairngorms (McClatchey 1996) make the frost susceptible new growth of *Quercus,* usually beginning in April, likely to suffer damage, making natural growth unlikely anywhere in the Mar Lodge valleys.

Movement of *Quercus* and other thermophilous taxa to Geldie Lodge is unlikely from Glen Feshie or Glen Tilt. The Feshie-Geldie watershed is 540m and though the Geldie-Tilt watershed is 450m, the gully connecting them is narrow, unstable and exposed. The most likely route is from upper Deeside; the likelihood of this is discussed elsewhere (Chapter 7). The relatively high, wide open valley makes the site ideal to receive a relatively strong regional pollen signal. All three taxa increase their percentage and concentration as the canopy fragments, implying long distance input.

Taxa in the field layer are in agreement with fluctuating canopy cover. *Calluna*, *Vaccinium*, *Myrica*, *Empetrum* and Poaceae percentages increase as those of arboreal taxa decline. Open conditions are strongly indicated by *Empetrum*, which exceeds 2% TLP in the middle of the zone, but *Calluna* has the biggest increase and dominated the field layer. Poaceae is increasingly important, accompanied by sporadic appearances of herbs including Asteraceae, *Filipendula* and *Potentilla*. Areas of open grassland are most likely to have been, as now, on the floodplain around the rivers (Figure 3.9). The alternative position for grassland, under the shade of a canopy too dense for *Calluna* to thrive, is unlikely initially, as *Calluna* percentages are high. Towards the top of the zone, when the percentage of most Ericales declines, the Poaceae percentage increases slightly, suggesting that under the canopy, grassland may have been an become important niche. *Hordeum* type grains recorded at *c.* 7500 cal BP are from wild grasses.

The position and character of Geldie Lodge, a wide, open valley, without steep valley sides, relatively close to the tree-line, would make the site attractive to early human hunters (Simmons 1996). The combination of site, high charcoal totals, oscillations in arboreal taxa, particularly *Pinus* percentage and influx, and the importance of many open ground taxa indicate that disturbance by Mesolithic people was possible. Many instances of early human occupation are supported by more consistent occurrences of pollen taxa indicative of disturbance, for example, *P. lanceolata*, *Melampyrum* and *Artemisia*, (Simmons 1996, Simmons and Innes 1996c) often together with increases of charcoal. This is not always the case as some disturbance phases have no increases in charcoal (Simmons and Innes 1996b, Hornberg *et al.* 2004). Other disturbance phases, particularly in north west Scotland and northern Sweden, are shown by a shift to *Calluna* and Poaceae rather than herb taxa (Bohncke 1988, Edwards 1998, Hornberg *et al.* 2004). The possibility of the Geldie sequence being a cultural landscape from the outset, and possible reasons for initiation of blanket peat accumulation are discussed in Chapter 7.

lpaz GL2, 105-129cm, *c*. 6080-7030 cal BP

Pinus sylvestris-*Sphagnum*-*Betula*-Poaceae

Basin environment

From c. 7040 to 6850 cal BP *Sphagnum* has two peaks in excess of 50% TLP plus Cryptograms, in excess of Huntley and Birks' (1983) estimate for the minimum for *Sphagnum* in a raised or blanket mire. Thereafter it declines to less than 10% TLP plus spores. Evidence consistent with a drying mire surface is also provided by the absence of Cyperaceae pollen from several levels in this zone and the decline in light transmission from more than 40 to 23% between *c.* 7040 and 6540 cal BP.

Fire

Charcoal totals are very low apart from a peak in all particle classes between *c.* 6620 and 6660 cal BP. Low totals above and below this peak mean the ratio of large to small particles is of little interpretative value. In levels with significant numbers of charcoal particles the ratio is not significantly higher than elsewhere in the sequence (Figure A.3d). There are no levels containing large particles of charcoal. Between *c.* 6540 and 6660 cal BP fire was more important in the landscape and may have affected the local vegetation.

Vegetation

Pinus was present locally; stomata are present in most levels. *Betula* was again present, at least initially. From *c.* 7030 to 6700 cal BP *Betula* and *Pinus* (around 70-80% TLP) formed a closed canopy within the local area. *Pinus* influx is consistently around the values associated with dense woodland by Seppa and Hicks (2006) and Jensen *et al.* (2007), and approaches the higher influx found by Hattestrand *et al.* (2008). This indicates denser woodland than in lpaz GL1, but as in lpaz GL1 *Pinus* values undergo an oscillation.

Betula also declines gradually. At the top of the zone *Betula* may still have been present locally; its percentage drops to around 13% TLP, found by Shaw (2006) to indicate local presence.

Declines of *Betula* and *Pinus* are associated with the charcoal peak (*c.* 6540 and 6660 cal BP). Percentage declines are clear but concentration and influx declines are even greater. At *c.* 6540 cal BP, *Pinus* influx is around the value Seppa and Hicks (2006) associate with regional influx but the presence of stomata show that percentage values better reflect local presence at this time. Stomata are absent only at *c.* 6700 cal BP, showing local disappearance of *Pinus* from around the core site for up to *c*. 120 cal years, preceding the decline in pollen. It is possible that *Pinus* individuals remained on dry ridges to the west of the core site or on the modern site of the Geldie Lodge building itself (Section 3.3.4), but also possible that trees were outside even the extra-local area. Percentages of *Alnus*, *Quercus* and *Ulmus* increase slightly, but not sufficiently to invalidate the conclusions from GL1. Increases occur during canopy fragmentation and are from long distance input.

Heaths virtually disappeared from the area. *Calluna* and *Empetrum* might be expected to benefit from more open conditions, but grassland increased instead of heathland. At the top of GL1 Poaceae was important and the family continues to increase in GL2; between *c.* 6420 and 6660 cal BP Poaceae reaches 40% TLP and has high concentrations. *Potentilla* type and *Filipendula* are fairly common throughout the sequence but are particularly important in this zone. Asteraceae and *Galium* type pollen are also present. Simultaneous occurrence of Asteroideae, Chichoriodeae, *Cirsium* type, *Galium* type, Ranunculaceae, *Stellaria* type and *Potentilla* type are clearly linked with grazing on a local scale according to Mazier *et al.* (2006). The extent to which sporadic appearance of some of these taxa can still be linked with light grazing is unclear.

Decreased charcoal values between *c.* 6700 and 7000 cal BP might be interpreted as decreased human impact. At this time people are regarded as having a wide range of potential impacts on their environment, including canopy manipulation with or without the use of fire, and disturbance of other components of the vegetation (Blackford *et al*. 2006). Changes to enhance or create opportunities for hunting of wild animals (Simmons 1996) are commonly cited, though changes favouring plants are less routinely identified. It is possible that dense woodland, relatively near the tree-line would have been attractive for hunting and so been subject to change. The fragmentation to grassy clearing between *c.* 6500 and 6700 cal BP is associated with a short charcoal peak very likely to be from local fire, which could be either natural or anthropogenic. Fire in the more highly resiniferous pine woodlands is much more likely than in other British woodlands, and could have led to the disintegration of woodland. However vegetation close to the Geldie Burn today is dominated by grasses (Figure 3.9); closer proximity of the river may have led to conditions favouring Poaceae, rather than Ericales, resulting in natural woodland fragmentation.

lpaz GL3, 81-105cm, *c.* 4930-6080 cal BP

Pinus sylvestris-Betula-Sphagnum-Calluna vulgaris

Basin environment

There is a single level (*c.* 5280 cal BP) with a decreased LOI values, but no other indication of allochthonous sediment input. Light transmission also increases slightly at *c.* 5280 cal BP; this may be linked to changes in mineral matter, but comes during a longer trend to increasing light transmission values (Section 6.2) between *c.* 4770 and 5860 cal BP. The inferred increase in surface wetness coincides with low *Sphagnum* percentages, however. *Sphagnum* is important at the base of the zone but almost disappears between *c.* 4870 and 5760 cal BP. Cyperaceae are relatively unimportant, but the consistent presence of *Polypodium vulgare* is in agreement with damp or shady conditions (Stace 1991). The weight of evidence favours a slightly wetter mire surface.

Fire

Charcoal totals are typically low and at more consistent values in lpaz GL3. Totals are slightly higher between *c.* 5670 and 5950 cal BP, and within this interval (*c.* 5760 cal BP) several large particles are identified (Table 6.8), indicative of very local fire. The preceding levels (*c.* 5860 to 5950 cal BP) have similar abundances of charcoal and the ratio of large to small particles increases (from 0.1, to 1.0, Figure A.3d), suggestive of more proximal fire.

Table 6.5 Large charcoal particles found within GL3

Stratigraphic level (cm)	Length of longest axis (μm)	Total number of micro-charcoal particles	Ratio of large to small particles
98	250 (x2), 270, 300	58	1.0

Vegetation

From *c.* 5180 to 5760 cal BP, *Pinus* percentages are between 20 and 30% TLP, open woodland according to O'Sullivan (1976) and Shaw (2006). Subsequent increases in percentages (from 40-50% TLP) are indicative of canopy closure. *Pinus* concentration falls lower than in previous zones and is variable. Several single level increases occur in the concentrations of *Betula*, *Alnus* and *Quercus*. *Calluna*, *Empetrum*, *Myrica*, *Pyrola* and *Vaccinium* share peaks at *c.* 5580 and 6040 cal BP. This suggests that fluctuations in concentration are related to changes in the rate of sediment accumulation not vegetation change.

Pinus influx is also variable, typically at or above the values associated with scattered or open woodland in Scandinavia (Seppa and Hicks 2006; Jensen *et al.* 2007). Stomata disappear at the base of the zone, but reappear at *c.* 5380 cal BP. *Pinus* percentages are lower when stomata are absent and recover when stomata reappear. *Betula* falls to percentages close to local absence after *c*. 5950 cal BP. Concentration and influx are variable but do not decline until after *c*. 5180 cal BP.

Woodland certainly became more open, though the absence of stomata is in agreement with *Pinus* individuals close to the core site (Dunwiddie 1987) and the continued high concentration values are in agreement with some proximal trees. As in GL2 *Pinus* could have been present within approximately 300m of the site; for example, on the dry ridges that run at right angles down to the Geldie Burn or the site on which the ruin of Geldie Lodge now stands (Section 3.3.4). These sites could have supported stands of trees when conditions on the mire itself were such that *Pinus* growth or re-generation was inhibited, contributing up to 50% of the arboreal pollen (Sugita *et al*. 1999, Bunting *et al.* 2004). Percentages of *Quercus* and *Ulmus* decline, particularly after *c*. 5760 cal BP. Pollen from these taxa remain as long distance input, as does *Alnus*. *Alnus* percentages of nearly 10% TLP at the base of the zone do not indicate local establishment (Bunting 2003, Shaw 2006).

Increases in heaths are generally in agreement with an opening canopy. In lpaz GL3 Poaceae is scarce and heaths, *Calluna*, *Empetrum* and *Vaccinium*, are more important. Herbs associated with grassland in GL2 also decline, though they do not disappear. *Calluna* shows the most distinctive increase, in phase with the decline and recovery in woodland. *Vaccinium* values are variable but exceed 5% TLP intermittently during the *Calluna* increase, suggesting that areas of relatively dense woodland remained. *Empetrum* exceeds 2% TLP after *c*. 5750 cal BP, but only as the canopy begins to close again and *Calluna* is in decline. This appears contradictory but may reflect local interactions between *Calluna* and *Empetrum*. *Myrica* and *Pyrola* type increase slightly. *Pyrola* type pollen is probably derived entirely from *Pyrola* spp. in the vegetation assemblage; the other main taxon within the type, *Moneses uniflora,* is a lowland plant, growing below 300m (Preston *et al.* 2002). *Pyrola minor* is found in a variety of situations, but *P. media* and *P. rotundifolia* are associated with open *Pinus* woodland or heath derived from *Pinus* woodland.

Canopy fragmentation should allow increases in long distance pollen input, which could be apparent as increased palynological richness. Palynological richness shows least inter-level variability in this zone, but it declines as woodland declines and increases as woodland recovers. This is less supportive of increased long distance input but is supportive of increased biodiversity in established woodland.

The combination of strong presence of *Sphagnum* and local fire may have disrupted *Pinus* growth or regeneration (Section 2.3), providing conditions better exploited by *Calluna* and other heaths. With the possible exception of *Vaccinium,* arboreal and non-arboreal pollen percentages are in agreement with open *Pinus* woodland. Once established heaths including *Calluna* may also be able to check the re-colonisation of the mire by *Pinus*. (Zackrisson *et al*. 1995, Bonan and Shugart 1989, Berglund *et al*. 2004).

lpaz GL4, 70-81cm, *c*. 4100-4930 cal BP

Pinus sylvestris-Sphagnum-Pine stomata-*Betula*

Basin environment

With initial percentages around the values found by Huntley and Birks (1983) to be indicative of *Sphagnum* mire, *Sphagnum* became the dominant component of the mire. From *c.* 4770 cal BP to the top of the zone the mire may have dried, as *Sphagnum* percentages decreased. Cyperaceae, with a small RSAP (Bunting 2003), increase slightly suggesting increased mire surface wetness, but percentage light transmission also decreases in agreement with a slightly drying of the mire.

Fire

Total numbers of charcoal particles are low. There are no levels with large charcoal particles. Fire is unlikely to have been important in the local or extra-local landscape.

Vegetation

Percentages of *Pinus* suggest the development of a semi-open canopy (30-40% TLP). Stomata are present in all levels, indicating local presence of *Pinus*, together with *Betula*, which has pollen percentages of up to 20% TLP. Concentrations of *Pinus* and *Betula* are low, but influx is within the range found to indicate mixed birch-pine woodland by Hattestrand *et al.* (2008) and Jensen *et al.* (2007). *Pinus* is likely to have grown directly on the mire surface as well as elsewhere in the valley. *Betula* probably also grew on or very close to the mire, and *Corylus* may have been present locally as it exceeds 5% TLP (Huntley and Birks 1983).

Quercus (more than 5% TLP) and *Ulmus* (3-4% TLP) exceed values associated with local presence by Huntley and Birks (1983), but not by Shaw (2006) who found both taxa to be over-represented in the pollen record. *Ulmus* in particular can exceed 2% TLP with no local presence (Shaw 2006). *Alnus* values are between 5 and 10% TLP, as before from regional sources. Although a denser tree canopy would tend to exclude long distance pollen input this is a more acceptable interpretation than local *Alnus* presence in such a high and exposed location.

Heaths preferring open conditions (*Calluna*, *Empetrum* and *Pyrola*) are almost absent in the middle of the zone. *Vaccinium* also declines but more slowly than other heaths. Herb taxa including Poaceae, Cyperaceae and *Filipendula* become slightly more important from the base of the zone. *Potentilla* type remains at about the same percentages as GL3, in agreement with a *Sphagnum* dominated mire and wet herb grassland. *Sphagnum* could have interfered with germination of *Pinus* seeds (Malmer *et al.* 1994; Section 2.3) potentially curtailing *Pinus* regeneration. If this occurred, the only evidence is the increase in *Betula*.

lpaz GL5 42-70cm, *c.* 2620-4330 cal BP

Pinus sylvestris-Calluna vulgaris-Betula

Basin environment

Sphagnum declines to low percentages but the appearance of *Drosera rotundifolia*, typically found growing with *Sphagnum*, suggests *Sphagnum* was still present. The preference of *Drosera* for open ground (Stace 1991) suggests an open mire. The upward trend in percentage light transmission, from 25% to 35%, may indicate a significant increase in surface wetness, potentially affecting the viability of taxa poorly adapted to wetter conditions.

Fire

The base of GL5 marks the end of the period of consistently low charcoal totals. Charcoal proportions are higher between *c.* 3520 and 3760 cal BP. There are very large particles of charcoal at *c.* 3760 and 4220 cal BP (Figure 6.6) and the ratio of large to small particles approaches 1 at *c.* 3520 cal BP (56cm). Fire is important in the local and extra local landscape, at the base and middle of the zone, but less important after *c.* 3520 cal BP.

Table 6.6 Large charcoal particles found within GL5

Stratigraphic level (cm)	Length of longest axis (μm)	Total number of micro-charcoal particles	Ratio of large to small particles
56	140	325	0.9
60	240	135	0.7
68	260	85	0.4

Vegetation

The *Pinus-Betula* woodland of GL4 continued into the base of GL5. Stomata show *Pinus* to be locally present, along with *Betula*, at the base of the zone. However, combined influx values of about 1500 grains cm^{-2} yr^{-1}, associated by Jensen *et al.* (2007) and Hattestrand *et al.* (2008) with mixed woodland decline after *c.* 3990 cal BP. After *c.* 3280 cal BP, *Betula* percentage drops to around the levels found by Shaw (2006) to indicate local absence and *Pinus* percentage collapses from 35% to around 15% TLP. This increase in influx is short lived, after *c.* 3990 cal BP *Betula* pollen declines; however *Betula* may have remained locally present throughout the zone, perhaps as a tree-line species or along stream banks. *Pinus* remained in the local area until *c.* 3030 cal BP when the last stomata are recorded. After this *Pinus* may have persisted in the extra-local area, perhaps on the drier ridges (Section 3.3.4), but by the top of the zone *Pinus* was not present locally. There are no increases from other arboreal taxa indicative of increased extra-local expansion.

There is a good correlation between increased importance of fire in the landscape and the decline of arboreal pollen, particularly of *Pinus*. As arboreal pollen decreases, *Calluna* and *Vaccinium* increase, other heath taxa do not change much and there are also interruptions to the increases of *Calluna*, including in concentration, associated with charcoal peaks between *c.* 3030 and 3280 cal BP. *Empetrum* increases slightly after *c.* 3030 cal BP and Poaceae remains as important as it was in GL4 until about the same time. It is possible that a few trees remained scattered within *Calluna* heath.

The percentages and concentrations of Poaceae are much smaller than in GL2, but are associated with grains of *Hordeum* type. *P. lanceolata* appears for the first time (less than 1% TLP) at *c.* 4000 cal BP. After *c.* 3200 cal BP, when *P. lanceolata* values become more consistent, percentages are only 1-2% TLP, but are accompanied at *c.* 3200 cal BP by Asteraceae. *Potentilla* type is also slightly increased before *c.* 3200 cal BP and is consistently present after this. Asteraceae, *Potentilla* type and *P. lanceolata* are included in the suite of taxa associated with grazing activity by Mazier *et al.* (2006). *P. lanceolata* at these values probably reflect only regional input but Asteraceae and *Potentilla* type are regarded as good local indicators (Mazier *et al.* 2006). This combination of pollen taxa, together with relatively high charcoal percentages makes human presence likely, especially after *c.* 3280 cal BP.

lpaz GL6 12-42cm, *c.* 600-2620 cal BP

Calluna vulgaris-Vaccinium-Empetrum

Basin environment

The data suggest a similar environment to that found today. The mosaic around the core site consists of *Sphagnum* pools with *Calluna*, Cyperaceae and Poaceae. The local mire may have dried slightly: *Sphagnum* has declined slightly relative to lpaz GL5, though *Drosera rotundifolia* and *Sellaginella sellaginoides* are now present. Cyperaceae becomes more sporadic and percentage light transmission declines between *c.* 2620 cal BP and 1000 cal BP also in agreement with a drying surface. Increases in percentage light transmission after *c.* 1000 cal BP, are likely to relate to changes across the acrotelm-catotelm boundary (Tisdall 2003).

Table 6.7 Large charcoal particles found within GL6

Stratigraphic level (cm)	Length of longest axis (μm)	Total number of micro-charcoal particles	Ratio of large to small particles
20	250 (x2)	548	0.5
36	220, 250, 300	298	0.4

Fire

Charcoal is very common throughout the zone. There are consistently large totals of particles, including 2 levels (*c.* 1170 and 2260 cal BP) with very large particles (Table 6.7). Local fire is very likely at these levels, and at *c.* 1480 cal BP (24cm) and *c.* 2520 cal

BP (40cm), where high totals and high ratios of large to small particles. It is possible that fires passed directly over the sample site. Charcoal becomes less important after *c.* 1170 cal BP.

Vegetation

Pinus was no longer present. Pollen percentages, concentrations and influx are at levels considered to be long distance input and there are no stomata. *Betula* may have been present locally until *c.* 1200 cal BP. *Betula* percentage and concentration values are initially similar to lpaz GL5. After *c.* 1450 cal BP percentages fall below 15% TLP, and after *c.* 1170 cal BP concentrations abruptly drop, *Betula* pollen is derived from extra-local or regional sources. The landscape probably looked similar to today.

Heath taxa exceed 60% TLP throughout the zone with *Calluna* as the most important taxon and *Vaccinium* as the main secondary genus. As other Ericales increase after *c.* 1000 cal BP, dwarf shrubs comprise nearly 90% TLP. The dominance by *Calluna* probably underestimates the local variety of species slightly, however though palynological richness initially declines, it recovers from *c.* 1730 cal BP.

Poaceae is still relatively important, suggesting a similar position to today, principally along riversides, as well as on the mire itself. The lower percentages of Poaceae make *Hordeum* type grains more likely to have derived from crops, at *c.* 2000 and 1730 cal BP. *P. lanceolata* continues to be relatively important, especially before *c.* 1450 cal BP. These taxa suggest human activities, including cereal cultivation, probably away from the local area, on valley sides, removed from potential flooding by rivers.

There is less evidence for human pastoral activity than in lpaz GL5, although there are single level appearances of bare ground herbs, *Artemisia* and *Cirsium* type, *Potentilla* type is less important. Declines in *P. lanceolata* and Poaceae after *c.* 2260 cal BP and in Charcoal after *c.* 1170 cal BP also support a decrease in human activity.

7 Discussion and conclusions

7.1 Content and organisation of this chapter

Discussion is based on the questions asked in Chapter 2 (Section 2.3 and 2.4) and is approached chronologically. Comparisons are made between Mar Lodge and other areas of the country because this is critical for assessment of the mechanisms of colonisation by *Pinus*, including seed production and dispersal, germination and establishment of *Pinus* (Section 2.2). Comparisons with Glen Affric and other areas with similar pollen and stomatal studies are particularly important in this exploration. This discussion is preceded by consideration of the conditions and timing of peat inception at the three sites and succeeded by questions surrounding the expansion and origin of woodland in Mar Lodge.

The evidence for diversity of plant communities within pine woodland in Scotland is addressed, with reference to the use of palynological richness, and in considering the role of other trees within pine woodland. An attempt is made to use pollen data to understand the physical appearance of the now-lost primary woodland, of increasing interest to archaeologists (Austin 2000; Tipping 2002). The structure of the woodland is fully considered, and includes discussion of temporal correlation of the synchroneity or diachroneity of fragmentation and disappearance of pine woodland. The discussion is completed with a consideration of possible prehistoric human impact on the plant communities at Mar Lodge.

7.2 Inception and accumulation of peat at the three sites

The Doire Bhraghad basin is likely to be a glacial kettle hole set within glacial and glacio-fluvial deposits in Glen Lui; as it’s location is considerably beyond late-glacial ice limits (Everest and Kubik 2006), the basin is likely to be a formed during deglaciation. The age of the base of the pollen stratigraphy sampled and investigated in Chapter 4 is estimated at *c*. 9800 cal BP, in the early Holocene. However, deglaciation is believed to have occurred much earlier, by *c*. 16000 cal BP (Everest and Kubik 2006, Clark *et al*. in press). Initial sediment accumulation might have been minimal because of the small basin size and absence of inflowing streams but this would be true in the early Holocene as well. A major rise in groundwater in the early Holocene, might have kick-started peat inception and as the sediment stratigraphy is similar throughout the basin (Figure 4.4), sediment accumulation may have commenced at this time across the whole base of the hollow, with more rapid accumulation in the deeper parts of the basin.

Sediment at Geldie Lodge, part of a blanket of peat covering the surface of an alluvial fan, differs in character and origin from the two other basins, and requires more discussion. Blanket peat is not limited to flat ground or low angle slopes; in western Scotland at least, peat tends to form on slopes up to 15^{o} (Langdon and Barber 2005). Peat inception of the core sample from Geldie Lodge is estimated at *c.* 7550 cal BP but the high inorganic content of the basal deposits indicates *in situ* mixing of basal peat with pre-existing mineral soil (Section 6.2). Sediment reaches sustained high LOI values, in excess of 90% and regarded as ‘wholly organic’ by Charman (1992), before *c.* 7000 cal BP (Figure 6.1). It is not clear, however, whether the focus of peat accumulation was at Geldie Lodge itself or if peat growth was initiated elsewhere on the slope and spread over the sampled site. During this initial period (lpaz GL1) the vegetation around Geldie Lodge changed from semi-open *Pinus-Betula* woodland, to open *Pinus* woodland with *Calluna*, before reverting to semi-open woodland. Simmons and Innes (1996a, b and c) argue that in the North York Moors people disturbed woodland, leading to peat inception. In Sutherland, Charman (1992) links peat inception with surface wetness and vegetation change, but the latter was linked to reduction of (*Betula*) woodland, probably by people. The main evidence pertaining to anthropogenic activity during this earliest vegetation oscillation at Geldie Lodge are the high charcoal percentages, but this association should perhaps be treated with caution (Tipping 1996).

Inception of peat at Geldie Lodge is later than at the nearest radiocarbon dated sites in Gleann Einich (Coire a Phris Ghiubhais, *c.* 8030 cal BP, Allt a Phris Ghiubhais *c.* 8250 cal BP and Lochan Odhar, *c.* 8785 cal BP, Binney 1997). Binney cites increased effective precipitation as causal. This difference in age may mean that peat began to form at Geldie Lodge as a result of localised changes in fluvial activity, that is, the cessation of mineral sediment deposition on the alluvial fan, the absence of erosion triggered peat formation on an already wet surface. Nonetheless, it is very likely that increased surface wetness triggered peat inception at Geldie Lodge; a rising water table at Geldie Lodge may have been due to increased effective moisture availability.

MacDonald *et al.* (2006) found that peat inception across the circum-arctic region increased rapidly between *c.* 12000 and 8000 cal BP, a period of increased temperatures and higher summer insolation. Peat inception may also have been linked with human activity and vegetation disturbance independent of climate. Tallis (1991) associated peat inception with wetter climate, but vegetation change, soil deterioration and human activity were also implicated. In the Pennines, Tallis (1991) identified three distinct periods of peat accumulation, at *c.* 10200 cal BP, between *c.* 8350 and 7850 cal BP and at *c.* 6300 cal BP. peat inception at Geldie Lodge is does not coincide with these periods but Langdon *et al.*'s (2003) climatic reconstruction from the Pentland Hills commences at *c.* 7500 cal BP, which itself may have climatic implications, and shows a major shift to wetter conditions at *c.* 6650 cal BP. Langdon and Barber (2005) emphasise the coherence of change in bog surfaces in Scotland but also note regional differences, particularly between northern and southern Scotland.

In northern Scotland, Anderson (1998) and Anderson *et al.* (1998) did not identify a shift to wetter climate at the time of peat inception at Geldie Lodge. Dubois and Ferguson (1985) found ‘pluvials’ at *c.* 8200 and 7200-6600 cal BP, suggesting lower surface wetness, but while Dubois and Ferguson (1985) regarded D/H ratios as indicative of precipitation (Section 2.5.2), others (Yapp and Epstein 1982, Gray and Song 1984, Tang *et al.* 2000) do not agree; Dubois and Ferguson’s ‘pluvials’ may indeed mean the opposite - periods of drier climate. This would place peat inception at Geldie Lodge within a wetter period. The widely identified climatic cooling at *c.* 8200 cal BP (Kobashi *et al.* 2007) is potentially linked with peat inception, though not directly as it is regarded as having been cool and *dry* (Alley and Augustsdottir 2005, Kobashi *et al.* 2007). Peat accumulation at Geldie Lodge occurred in the wetter period following this event. It may have been in response to complex factors: localised ones including vegetation change, stream activity and perhaps some human activity, but coinciding with a regionally wetter climate.

Accumulation of peat at White Bridge began when the River Dee ceased to flow down the northern side of the valley. This may have been related to a shift to a wetter climate between *c.* 3900 and 3500 cal BP identified by Anderson *et al.* (1998).

Summary

Peat accumulation at Doire Bhraghad probably begins in the early Holocene, though accumulation may have begun soon after ice melted following deglaciation at *c.* 16000 cal BP, stratigraphically below the sequence sampled for pollen. The base of the sampled sequence does not represent a change in the sedimentary environment, but may represent an increase in mire surface area as the basin infilled.

There is no evidence to suggest that the base of the Geldie Lodge sequence is the oldest peat in the area. Though a thicker peat section about 300m to the east may represent accumulation prior to *c.* 7550 cal BP, peat accumulation initiated at Geldie Lodge from this time, probably as wetter conditions increased effective moisture on the alluvial fan.

Peat accumulation at White Bridge also correlates with a shift to a wetter climate just after *c.* 4000 cal BP. But peat inception is specifically possible at White Bridge when the River Dee abandons its channel.

7.3 Plant communities and soils at Doire Bhraghad prior to *Pinus* colonisation

An understanding of the plant communities and soils prevalent before the arrival of *Pinus sylvestris* might help identify the competitive advantages that *Pinus* possessed. Doire Bhraghad is the only pollen and sediment record in Mar Lodge that shows this as peat at Geldie Lodge and White Bridge began accumulating after the arrival of *Pinus* in the area. The vegetation assemblage at the start of the pollen record appears to have been an homogeneous, partly open *Betula* woodland with *Corylus* and *Salix* (Section 4.5, lpaz DB1). This is similar to other core areas of *Pinus* in Scotland (Birks 1972, O'Sullivan 1974a and 1976, Froyd 2005). The tree canopy cover was sufficiently open around Doire Bhraghad to allow an understorey of grasses and herbs to flourish, rather than heaths (except *Empetrum*), probably on a mull, relatively base rich soil rather than an acid mor humus. Most herbs indicate relatively damp conditions, in contrast to the dry substrates preferred by *Empetrum*, and the ground flora may be reflecting wetter soils in the basin below dry soils across the valley floor.

Betula is initially the dominant taxon, comprising up to 50% TLP. Influx values are easily in excess of sub-alpine birch woodland according to Jensen *et al.* (2007) and around the values for birch forest found by Hattestrand *et al.* (2008). This description suggests dominance by *Betula* but probably not the formation of closed canopy. Nonetheless, the consistency of *Betula* in the pollen assemblage is indicative of a taxon which is widespread and had limited competition from other plants, particularly in the canopy. *Betula* was so strongly established in the landscape that even during the oscillation in *Pinus* percentages from *c.* 9590 cal BP (below), *Betula* influx was unaffected.

Percentages of 5-10% TLP suggest that *Corylus* was not common around Doire Bhraghad (Figure A.1a), in marked contrast to many other localities in Scotland at this time (Birks 1989; Tallantire 2002). However, *Corylus* at the nearby Morrone Birkwoods (425m OD, Huntley 1994) never exceeds 5% TLP, and Binney (1997) does not regard *Corylus* as an important species even at her lowest site, Allt a Phris Ghiubhais (500m OD). This suggests that *Corylus* may have been relatively scarce in this area.

Corylus may have been more abundant than inferred from pollen percentages, however, if it was at the edge of its climatic tolerance, particularly as frost can restrict pollen and fruit production. At Mar Lodge today, frosts are possible in any month (Section 3.1.4) and it is likely that in the early Holocene, conditions were similar (Davis *et al.* 2003). Repeated spring frosts may have interfered with the flowering of *Corylus* (Tallantire 2002, Preston *et al.* 2007, Seppa *et al.* 2007) or with the development of saplings and catkins in the autumn (Tallantire 2002). According to McClatchey (1996) the harshest frosts in the valleys around the Cairngorm plateaux are during temperature inversions (Section 3.1.4). These are common during the autumn and spring when anticyclonic weather patterns are dominant, and are exacerbated by the formation of frost hollows in the relatively enclosed valleys of upper Glen Dee and Glen Lui.

Pinus is able to grow in temperatures reaching -60°C (Steven and Carlisle 1959), giving it a competitive advantage over *Corylus* and colonisation by *Pinus* was probably on similar sites to those occupied by *Corylus*. The resultant shading of *Corylus* by *Pinus* would have further inhibited flowering and may have already begun at peat inception. Ultimately the relative scarcity of *Corylus*, the similar ecological preferences of *Corylus* and *Pinus* and climate conditions favoured *Pinus* and allowed it to exclude *Corylus*.

Salix is typically underrepresented in the pollen assemblage, making the low percentages found initially likely to indicate local presence (Shaw 2006). It is thought that *Salix* was mainly present on the ground to the south of the basin, but it may have been present in the basin itself (Section 4.5, lpaz DB1). The typical form of the shrub makes it an important component of the field layer, it's normal habitat being a wet environment.

Summary

The vegetation assemblage in Mar Lodge, prior to the appearance of *Pinus*, consisted of *Betula* woodland with *Salix* and some *Corylus*. *Betula* is the dominant arboreal taxa, probably forming a semi-open canopy, with *Corylus* and *Salix*. *Corylus* is less important in Mar Lodge than in many areas of Scotland at the time. This may have been a feature unusual to the local area, local climatic conditions, or simply due to the relatively high altitude. It is likely that a combination of unfavourable climate and competition from *Pinus* resulted in the relative scarcity of *Corylus*. *Salix* was probably initially a main understorey component. Ground flora consisted of Poaceae and other herbs, indicative of a relatively open woodland canopy. The combination of these canopy, understorey and ground flora indicates a damp, relatively base-rich soil.

Figure 7.1 Woodland stand dominated by *Betula*, approximately 200m^2, Dulnain Glen, Monaliadh Mountains, near Aviemore. *Pinus* stands, visible in the centre of this image, surround the area of *Betula*. The stand includes *Betula* at a range of maturities including saplings; despite the close proximity of mature *Pinus* there are no *Pinus* saplings. In contrast open *Calluna* heath between *Pinus* stands in the same area feature large numbers of *Pinus* saplings, suggesting that conditions in the *Betula* stand prevent germination or growth of *Pinus*.

7.4 First appearance of *Pinus*

7.4.1 Stomatal evidence for the first appearance of *Pinus* at Mar Lodge

Damp conditions within the Doire Bhraghad basin helped maintain openings in the *Betula-Salix* woodland, permitting colonisation by *Pinus* seedlings. Basin slopes provided the dry, aerated and warm edaphic conditions required for seed germination (Section 2.2). The relatively flat, uniform ground surrounding the basin may have been less inviting, the homogeneous terrain providing fewer openings in canopy cover, lowering the chances of seed germination and sapling recruitment. This topographic variation is suggested to mean that certain sites, such as Doire Bhraghad, would be preferentially colonised, but spread beyond such sites could have been slow.

The local occurrence of *Pinus* near Doire Bhraghad is attested by *Pinus* stomata, recorded from *c.* 9590 cal BP. Stomata define the very local presence of *Pinus* individuals, within 10-20m of the sampling site (Section 2.5.2; Parshall 1999). Pratt (2006a) found stomata recorded in all her modern samples in Abernethy Forest when *Pinus* grew within 20m, though there was no relationship between pollen and stomatal proportions.

Over the next *c.* 400 cal years there were complex fluctuations in the values of *Pinus* stomata and pollen. Stomatal counts are low before *c.* 9200 cal BP, typically less than five per sample. When the first stomata are recorded, *Pinus* pollen percentages are also low, around 13% TLP, but they rise and exceed 20% TLP by *c.* 9500 cal BP. At *c.* 9420 cal BP, when *Pinus* pollen percentages decline to less than 10% TLP, stomata cease to be recorded. Stomata are recorded again from *c.* 9330 cal BP but this does not coincide with an immediate increase in the proportions of pollen. Pollen percentages exceed 20% TLP only after *c.* 9250 cal BP, rising further to 40% TLP after *c.* 9150 cal BP. Without stomata there would be uncertainties as to the local presence of *Pinus* trees until *c.* 9200 cal BP. Nevertheless, stomatal data do no more than indicate local presence, potentially of just a single pine tree. The first stomatal record is the best evidence for colonisation of the very local area by *Pinus*. At Doire Bhraghad, this area is delimited by the top of the basin slope, at most 20m from the core site. *Pinus* could have been growing outwith this area before *c.* 9590 cal BP.

Derivation of information from fluctuations in the percentages and influx values of pollen and stomata is more complex. In common with other sites, fluctuations in stomata and pollen at Doire Bhraghad do not follow simple correlative patterns (see above). For instance, Froyd's (2005) stomatal counts from Loch an Amair in Glen Affric do not increase with increases in pollen proportions. The highest stomatal accumulation rates at Loch an Amair occur when pollen percentages and influx values fall. Similarly in east Glen Affric, at her PB site, Shaw (2006, Figure A2.1, page 352-354), found stomatal percentages continued to rise after pollen percentages peaked.

Consistent presence of stomata around a pollen site does not necessarily imply that *Pinus* was common in the landscape. As at Doire Bhraghad, a mire may represent one 'favourable' site for *Pinus*. The favoured location, perhaps far from a more abundant cohort of trees, may be in an area where seedling establishment on surrounding unfavourable soils is low. Germination of seeds several kilometres from a parent is feasible, but the chances of cross pollination and production of viable seeds decrease with distance from other *Pinus* individuals (Section 2.2). Thus production of viable seeds is unlikely for solitary pioneering individuals. Figure 7.1 illustrates the possibility of even semi-open *Betula* woodland appearing to restrict the chance of viable seeds falling on a favourable site and germinating. If initial production of viable seed is also low (it is probably not low in Figure 7.1), subsequent seedling recruitment will be very low.

A very small number of *Pinus* trees, or a single individual within *Betula* woodland, may also be under-represented in the pollen diagram. Sugita *et al.*'s (1999) pollen productivity estimates, using *Juniperus* as the unitary value, gave *Pinus* a relative pollen productivity of 2.74 and *Betula* a score of 4.29. This allows the possibility that *Pinus* might have been slightly more common in the landscape than suggested by pollen, with pollen from the more abundant *Betula* overwhelming the signal from *Pinus*. At Doire Bhraghad the comparative values of *Pinus* and *Betula* pollen suggest that even if *Pinus* was more abundant than it appears from its percentage values, it was still considerably less abundant than *Betula*.

The pattern of low percentages of *Pinus* pollen with consistent occurrence of stomata, as seen at Doire Bhraghad is difficult to interpret. *Pinus* trees may have been growing close to the core site, shedding needles (and stomata) but not contributing pollen. The scarcity of pollen is problematic as *Pinus* can produce pollen from two years after germination and usually within ten years (Section 2.2). Modern open woodland with *Betula* and *Sorbus*, probably similar to that described from Doire Bhraghad at *c.* 9590 cal BP, is unlikely to create conditions inhibiting pollen production by *Pinus*. In open situations *Betula* does not usually compete successfully for light with the much taller growing *Pinus*, but Edwards and Mason (2006) found that even in open woodland, initially *Betula* and *Sorbus* saplings far outnumbered those of *Pinus*. Subsequently *Pinus* saplings grew through, and came to dominate the broad-leaved canopy. Under a semi-open *Betula* canopy relatively thick, damp, field vegetation and leaf litter may have prevented development of the dry bare ground favouring *Pinus* germination. These conditions may have further reduced germination of an already limited number of viable *Pinus* seeds, preventing recruitment of *Pinus* saplings and slowing the rate at which *Pinus* numbers increased (Figure 7.1).

At Doire Bhraghad, declines in pollen percentages, beginning at *c.* 9420 cal BP, may mean that the initial rise in pollen was derived from very local trees. If the initial peak in *Pinus* percentage and influx values was due to pollen derived from local, extra-local or regional inputs, the disappearance of trees from around the basin would make little difference to pollen counts. The oscillation in pollen proportions before *c.* 9200 cal BP indicates that the first trees either failed to produce viable seeds or dropped viable seeds in unfavourable niches. The decline in pollen from *c.* 9420 cal BP is in agreement with the interpretation of *Pinus* having a presence only around the Doire Bhraghad basin itself. *Pinus* was not, however, common in the local or extra-local areas (defined in Section 3.4). As long as *Pinus* was uncommon in the landscape, the possibility of it generating viable seeds which germinated successfully remained low. The initial oscillation in pollen percentages and stomatal occurrence can be regarded as an unviable or failed colonisation of the Doire Bhraghad basin.

Summary

The first record of *Pinus* stomata at Doire Bhraghad (*c.* 9590 cal BP) indicates the first appearance of *Pinus* within the basin. It does not necessarily indicate the first appearance in the local or extra-local area, nor does it imply that *Pinus* was a common feature of the vegetation in Glen Lui. Low *Pinus* pollen percentages suggest that *Pinus* was relatively sparse in the landscape until *c.* 9200 cal BP. An initial rise in percentage values and influx is thought to represent pollen production by trees or a tree immediately at the sampled location. Subsequent falls in pollen percentage and influx are indicative of a failure of *Pinus* to colonise the basin with a viable population. Superior competitive ability of *Betula* in a semi-open canopy may have restricted the availability of such favourable local niches.

7.4.2 First appearance of *Pinus* elsewhere in Scotland

The first appearance of *Pinus* from Loch an Amair, at *c.* 9930 cal BP (Froyd 2005, Froyd and Bennett 2006), from the first record of stomata, is the only first appearance in Scotland to precede that of Mar Lodge. The woodland assemblage into which *Pinus* appears is similar to that of Mar Lodge. Froyd (2005) was the first to demonstrate the presence of *Pinus* trees from stomatal data in the early Holocene, prior to increases in pollen percentages. Stomatal records at Froyd's sites, Loch an Amair and Dubh Lochan, precede rises in pollen by *c.* 1600 and 800 cal years respectively (Froyd 2005, Froyd and Bennett 2006).

Froyd's findings undermined some of what was thought about the early Holocene spread of *Pinus*. Froyd regards Godwin's (1975) model of arrival, establishment and expansion of a taxon as applicable to her assemblages. But reconciling the model from Loch an Amair with previous models is difficult, not least because pollen records alone can no longer be used to assess colonisation and establishment. The unanswered question from Froyd's (2005) study is: What is being shown by these palynological assemblages? The assemblage from Doire Bhraghad may help explain that the stomatal and pollen signals reflect two different ecological strategies of *Pinus* trees (Section 2.2), as a colonising tree and as a common woodland tree.

Though the first record of stomata precedes increases in *Pinus* pollen percentages at Doire Bhraghad, Lochan Amair and Dubh Lochan, assemblages from Torran Beithe (Davies 2003a), Abernethy Forest (Pratt 2006a and b) and Farlary (Tipping *et al.* 2008) do not record stomata prior to increases in pollen percentages (Section 2.6.4). The dissimilarity of the sedimentary environments at Doire Bhraghad and in Froyd's (2005) sites makes the similarity between these palynological assemblages more interesting.

As described in Section 7.4.1, the oscillation in pollen percentages at Doire Bhraghad (*c.* 9600 to 9200 cal BP) probably derives principally from pollen from local trees. The larger source area of the lakes at Loch an Amair and Dubh Lochan are more likely to record dispersed individuals of *Pinus* within the catchment, but less likely to record a small variation in pollen percentages such as seen at Doire Bhraghad. Consistent presence of stomata in either a mire setting or the lake setting need not indicate an abundance of trees in the landscape. Though neither Loch an Amair nor Dubh Lochan have inflowing streams, their diameter, 100 and 125m, give them considerably larger pollen source areas than the peat basin at Doire Bhraghad, increasing both the chance of recruitment of stomata and pollen from isolated individuals, and the chances of pollen from more abundant *Betula* masking pollen production by *Pinus*.

Lake shores provide create permanently open sites that favours *Pinus* colonisation; other ephemeral features such as canopy gaps provide more limited opportunity. A tree growing on a lakeshore has a high probability of contributing stomata to the palynological assemblage, but as long as such favourable locations remain sparse in the landscape, pollen percentages will remain low. Individuals occupying these isolated favoured sites are unlikely to produce viable seeds and hence seedlings, even if further sites are available (Section 2.2).

The extended duration when the combination of stomata and low pollen percentages are recorded in the assemblages from both Dubh Lochan and Loch an Amair may represent a series of *Pinus* individuals growing within the catchments, perhaps in different localities. Recruitment of seedlings into the population was rare but sufficiently common to maintain a viable population at the landscape level for an extended period. Only when some other perturbation affected the vegetation assemblage was *Pinus* able to become more important in the landscape (Section 7.5.2).

The similarity of Doire Bhraghad, Loch an Amair and Dubh Lochan and their dissimilarity from Torran Beithe, (10km west of Loch an Amair), are key to explaining the colonisation of a landscape by *Pinus*. Doire Bhraghad and Torran Beithe are small-diameter peat basins, with similar-sized pollen source areas, which emphasise local vegetation. The basin at Doire Bhraghad is regarded in this study as a favoured site, but colonisation by *Pinus* is still a chance process, *sensu* McVean (1963b), Bennett (1984) and Birks (1989). At Doire Bhraghad *Pinus* as a species remains as a series of separated individuals, occasionally producing successors as the chance of a suitable opening in the canopy coincides with the production of viable seeds. At Torran Beithe, the later first appearance of stomata could be explained in at least two ways. The chance process of colonisation may have occurred at the same time as a general increase of the abundance of *Pinus* in the landscape, suggesting that the expansion of woodland was led by local tree populations. Alternatively the basin may have been a more marginal site for *Pinus*, only being colonised once conditions were perturbed in favour of *Pinus*, this improvement of conditions could have been forced by changes to regional climate.

All four sites for which there are pollen and stomatal data (Doire Bhraghad, Loch an Amair, Dubh Lochan, Torran Beithe) show a similar period of time, *c.* 400 cal years, in which *Pinus* pollen percentages increase from around 5% to 40% TLP. In the three western sites the start of this increase, between *c.* 8600 and 7950 cal BP, is transgressive from east (Dubh Lochan, earliest) to west (Torran Beithe, latest), indicative of a migration of *Pinus* woodland to upper Glen Affric. This suggests that despite being viable at a landscape scale, the persistent presence of *Pinus* did not, of itself, lead to it becoming dominant. However this is now leading to a more detailed discussion of the expansion of *Pinus* woodland (Section 7.5.1).

The first records of *Pinus*, according to stomata and increases of *Pinus* pollen percentages, are clearly two different measures and for this reason it is appropriate to discuss them separately. Many studies base first appearance of *Pinus* on the increase of *Pinus* pollen percentages in the assemblage, the rational limit of pollen (*sensu* Smith and Pilcher 1973). Comparing appearance based on the increase in *Pinus* percentages at Loch Maree *c.* 9250 cal BP (Birks 1972) with appearance based on first record of stomata at Loch an Amair (Froyd 2005) is to compare dissimilar measures (Section 2.6.4). It is a comparison of different events: the record of colonisation of perhaps single individuals and the establishment of *Pinus* as a woodland species.

The increase in *Pinus* percentages from low values (5-10% TLP) to high values, equal to or more than 40% TLP, takes between *c*. 200 and 500 cal years at many sites (Section 2.6.4). With the exception of Huntley *et al.*'s (1997) first record from Lochan Oir, the use of pollen alone allows the possibility of a much earlier first record of *Pinus* had stomatal counts been made. Thus though the appearance of stomata at Loch an Amair is very early in the Holocene, *Pinus* pollen percentages remain below 5% TLP until *c.* 8400 cal BP. Subsequent increases in pollen percentages are rapid but still post-date the increases at Loch Maree by *c.* 800 cal years (Section 2.6.4). The start of increases in *Pinus* percentage at Dubh Lochan are also after those at Loch Maree, though by just *c.* 100 cal years.

Summary

Loch an Amair, in Glen Affric, is the only site to record stomata in a palynological assemblage earlier than at Doire Bhraghad; Dubh Lochan near Loch Ness has stomatal records from about the same time. Appearance of stomata preceding increases of *Pinus* pollen percentages is not necessarily the ‘normal’ succession; several other sites record stomata appearance and increases in *Pinus* percentage simultaneously.

Very early first appearances of *Pinus* at Loch an Amair and Dubh Lochan represent a series of *Pinus* individuals growing within the catchment which failed to give rise to large numbers of successors. The 1600 cal years that stomata are recorded at Loch an Amair before an increase in the pollen percentage, show that *Pinus* can be viable in the landscape without becoming an abundant woodland taxa. A combination of competition from pre-existing woodland species and possibly unfavourable climate, prevented the expansion of *Pinus* in the early Holocene.

Unlike Doire Bhraghad, Loch an Amair and Dubh Lochan, at Torran Beithe, stomata are not recorded prior to increases in *Pinus* pollen. This is regarded as a later chance process of colonisation or that Torran Beithe represented a more marginal habitat for *Pinus*, only supporting *Pinus* once changed conditions led to larger numbers of trees producing viable seeds in large quantities.

The spread of woodland between the three sites Dubh Lochan, Loch an Amair and Torran Beithe, between *c.* 8600 and 7900 cal BP seems to suggest a migration of *Pinus* dominated woodland across the landscape. This may have been facilitated by changes in climate leading to improved conditions but is best explained as a movement of *Pinus* into the area rather than increases of an extant population.

7.5 Expansion and origin of *Pinus* woodland

7.5.1 Expansion of *Pinus* woodland

Separation of the first appearance of *Pinus* and expansion of *Pinus* as a woodland species is relatively straightforward at Doire Bhraghad. Appearance of stomata at Doire Bhraghad at *c.* 9590 cal BP precedes sustained increases in pollen, showing that *Pinus* was present at least 400 cal years before becoming dominant. Stomata appearance in every level from this time interval could represent a single chance colonisation by a single tree: the oldest trees in modern pinewoods in Glen Affric were 260 years old (Edwards and Mason 2006) and the oldest documented pine tree in Scotland was over 330 years old when it blew down in 1951 (Steven and Carlisle 1959). The normal life span in Britain is 150-300 years, but the oldest recorded specimen in Sweden was over 700 years old. Rackham's (2001) proposal that trees are killed by, for example, a storm or fire, rather than dying of old age, suggests tree age is mainly an indicator of return frequencies for major storms or fires. Thus the delay in the expansion at Doire Bhraghad could have been in a single generation of trees. However, a brief increase in percentage and influx at Doire Bhraghad around *c.* 9500 cal BP (Section 7.4.1) suggests two generations. The first colonisation did not lead to an increase in local *Pinus,* but the second colonisation was part, or the start, of a general increase in local tree abundance. The second colonisers did not necessarily arise directly from the first. The two generations may represent two chance colonisations of the same site.

The first increase in *Pinus* pollen at Doire Bhraghad peaks at *c.* 9500 cal BP, coincident with Bennett's (1997) estimate of regional increase. The second increase of *Pinus* pollen at Doire Bhraghad, from *c.* 9200 cal BP is still earlier than Birks' (1989) estimate of the beginning of the rise to sustained values in Eastern Scotland (between *c.* 7900 and 6800 cal BP). Birks (1972) dates the increase in *Pinus* pollen percentages from Loch Maree to *c.* 9250 cal BP. Timing of the increase of *Pinus* percentages in Mar Lodge and Loch Maree are similar, suggesting that establishment of *Pinus* as a woodland dominant was at a similar time at both sites.

The vegetation assemblage at Doire Bhraghad prior to the increase of *Pinus* pollen percentages (*Betula* woodland with some *Salix* and *Corylus*, Section 7.3), may be atypical of Scotland but the subsequent replacement of *Salix* and *Corylus* by *Pinus* is more usual, as is the persistence of *Betula*. *Salix* may have remained in the vegetation assemblage at Doire Bhraghad until *c.* 5900 cal BP but after 9200 cal BP it was a more minor component, probably restricted to marshy ground to the south of the basin. It probably remained there, but was less important in the pollen assemblage as the closing *Pinus* tree canopy restricted regional input of pollen and emphasises local sources.

Although it is not clear why *Corylus* was initially scarce in the landscape at Mar Lodge, its seeming disappearance was probably a result of competition with *Pinus* (Section 7.3). Tallantire (2002) showed that when shaded woodland restricts *Corylus* flowering, the tree can persist in woodland by vegetative regeneration. This may have occurred at Mar Lodge, but the lack of increase in *Corylus* pollen percentages at *c.* 9330 cal BP, when *Pinus* percentages decline, suggests that *Corylus* had been excluded from the woodland.

The ground flora of Poaceae and other herbs associated with the *Betula* woodland was initially unchanged and changed only slowly thereafter. There are no indications of disturbance from charcoal or pollen records favouring the increase of *Pinus* in the Doire Bhraghad sequence and it is possible that the cool and damp conditions under the *Betula* canopy prevented rapid expansion of *Pinus* in the area. Increases in *Pinus* influx are not matched by decreases in *Betula* influx for up to 400 years, showing that *Betula* remained important in the assemblage, in agreement with competitive interaction between the two species.

In modern forest situations, *Betula* does not usually compete successfully for light with the much taller growing *Pinus*, but early in the Doire Bhraghad sequence this appears to have been possible (Section 7.4.1, Figure 7.1). Indeed as already suggested it is possible that the continued importance of *Betula* prevented a more rapid spread of *Pinus*. *Pinus* probably initially occupied gaps in the *Betula* canopy but when *Pinus* became dominant at *c.* 9200 cal BP, the roles of *Betula* and *Pinus* were reversed with *Betula* occupying gaps in the *Pinus* canopy. *Betula* remained in the local area, at reduced abundance until *c.* 8500 cal BP.

The ecology implied from the plant assemblage associated with the *Betula* woodland at Doire Bhraghad may have hindered the increase of *Pinus* (Section 7.4.1), but *Pinus* may also have suffered from a lack of the appropriate mycorrhiza (Section 2.2). In sub-optimal conditions the lack of mycorrhiza may interfere with growth sufficiently to prevent seedlings from maturing (Hornberg *et al.* 2004). It is unclear whether this is likely to have been a problem in deciduous-dominated woodland such as in the early Holocene at Mar Lodge, but is thought to be significant in modern Fenno-Scandian forest (Zachrisson *et al.* 2004, Berglund *et al.* 2004).

The sequence at Geldie Lodge shows neither the arrival of *Pinus* in the area nor the rise in *Pinus* pollen percentages. It is possible that increases in *Pinus* percentages occurred only shortly before the inception of peat accumulation. But at Torran Beithe and Loch an Amair in Glen Affric the increase in *Pinus* pollen percentages are just *c.* 500 cal years apart. This is still slower than Birks' (1989) estimates of migration, which would allow movement by *Pinus* between Doire Bhraghad and Geldie Lodge in just 100 years. The similar distances from Geldie Lodge to Doire Bhraghad and from Torran Beithe to Loch an Amair makes an increase of *Pinus* pollen at Geldie Lodge plausible at any time from *c.* 9100, but increasingly likely after *c.* 8700 cal BP. This assumes that the *Pinus* at Geldie Lodge originated from Doire Bhraghad rather than from Speyside (See Section 7.5.2).

Betula was locally present and remained a component of the local vegetation for much of the sequence. Declines in the *Betula* percentage from *c.* 7300 cal BP are linked to increases in that of *Pinus*, but variations in the concentration and influx of *Pinus* and *Betula* are positively correlated. This is in agreement with a competitive relationship between the two taxa occupying the same space, rather than from *Betula* occupying a higher treeline location. *Corylus* could have been present at peat inception but is likely to have been only sporadically present at best and *Salix* was probably locally present, as at Doire Bhraghad.

Separation of first appearance of *Pinus* and expansion of *Pinus* woodland from Froyd's (2005) sites is also straightforward. *Pinus* existed as a chance coloniser, in low but possibly stable numbers, for up to 1600 cal years at Loch an Amair and 800 cal years at Dubh Lochan. This time gap is indicative of several generations. The timing of increases in *Pinus* percentages, *c.* 8400 and 9100 cal years respectively, is sufficiently different from Doire Bhraghad and Loch Maree to suggest different forcing factors. Appearance and expansion at Torran Beithe occurred synchronously, and was later still, from *c.* 7950 cal BP.

At other sites in core areas of Scotland, where stomata are not included in the analysis, separation of appearance and expansion is not possible. The start of increases in *Pinus* percentages in Scottish sites is not synchronous, but occurred between *c.* 9250 and 7900 cal BP (Section 2.6.4). It is difficult to extract similar data from all studies, but for a selection of sites this has been attempted (Table 7.1). Apart from difficulties with ^{14}C dating in original studies, it should be noted that Birks (1972) and O'Sullivan (1976) based pollen sums on counts of arboreal pollen. O'Sullivan (1974a) stipulated this in his work from Loch Garten but was not explicit in the Loch Pityoulish stratigraphy (O'Sullivan 1976). The Loch Garten stratigraphy (O'Sullivan 1974a) is less thoroughly dated than the Loch Pityoulish study.

Table 7.1 Dates by which *Pinus* exceeds 5, 10, 20 and 40% TLP at various locations in Scotland.

Location	Author	Stomata date (*c*. cal BP)	Last date when *Pinus* comprises less than 5% TLP, (*c*. cal BP)	Date at which *Pinus* exceeds 10% TLP, (*c*. cal BP)	Date at which *Pinus* exceeds 20% TLP, (*c*. cal BP)	Date at which *Pinus* exceeds 40% TLP, (*c*. cal BP)
Loch Maree	Birks 1972	No	9250	9200		9000
Loch Pityoulish	O'Sullivan 1976	No	8900		8600	7900
Abernethy Forest	Birks and Mathewes 1978	No	8250		8100	8000
Loch Davan	Edwards 1978	No	8400		7600	7500
Torran Beithe	Davies 2003a	7950	8300		7950	7500
Dubh Lochan	Froyd and Bennett 2006	9600	9100		8800	8600
Loch an Amair	Froyd 2005	9950	8400		8200	8000
Farlary	Tipping et al 2008	7500	Before pollen sampling	8400	7550	7500
Doire Bhraghad	This study	9590	9600	9400	9200	9150

At Loch Maree (Birks 1972), Loch Sionascaig, Loch Craggie and Loch Clair (Pennington *et al.* 1972), and at Beinn Dearg (Binney 1997) initial increases in *Pinus* occurred at the expense of *Corylus*, with *Betula* remaining important in the vegetation (Section 2.6.7). Neither Birks (1972) nor Pennington *et al.* (1972) make specific comment concerning the conditions enabling the establishment of *Pinus*, but Binney regards dry conditions as key to the establishment of *Pinus* in gaps in the *Betula* canopy. The persistence of *Betula* suggests it remained able to regenerate within the denser canopy formed with *Pinus*. In contrast the decline of *Corylus* is in agreement with its requirement for gaps in the canopy.

There are similar scenarios in the sites on Speyside. At Loch Pityoulish (O'Sullivan 1976) and in Abernethy Forest (Birks 1970, Birks and Mathewes 1978) *Betula* remained important as *Betula-Pinus* replaced *Betula-Corylus* assemblages (Section 2.6.7). Only at Loch Garten did *Corylus* remain an important part of the pollen assemblage, regarded by O'Sullivan (1974a) as indicative of more open woodland.

Increases of *Pinus* in western Glen Affric were within a slightly more diverse assemblage, including *Betula*, *Sorbus* and *Populus*. This assemblage may not have included the canopy gaps that *Pinus* was able to exploit elsewhere. *Pinus* became more important in the vegetation at Torran Beithe only when the pollen assemblage suggests disturbance correlated with a drying phase from *c.* 8040 to 7470 cal BP (Davies 2003a).

Pinus at Mar Lodge began to dominate the assemblage earlier than in most parts of Scotland (Table 7.1) but later than in much of Fenno-Scandia (Section 2.6.5). This implies that different factors were involved in the establishment of *Pinus* woodland in Fenno-Scandia and in different parts of Scotland. At Doire Bhraghad the rise in *Pinus* pollen percentage and influx at *c.* 9200 cal BP just precedes a period of rapid climatic variability identified by Mayewski *et al.* (2004). This second *Pinus* rise is also just before a period of increased seasonality, decreased moisture availability (Allen *et al.* 2007) and lowered effective precipitation (Tipping 1996). All these events commence from *c.* 9000 cal BP.

Kullman (1995) and Kullman and Kjallgren (2000) suggest that *Pinus* was common in northern Fenno-Scandia by *c.* 10000 cal BP. In northern Finland, Seppa and Birks (2001) suggest that temperatures between *c.* 9900 and 8200 cal BP started slightly cooler, but ended around 1^{o}C warmer than today, with precipitation decreasing over the same period. These reconstructions are based on pollen assemblages that may generate circular arguments if increasing abundance of *Pinus* is used to indicate warmer and drier conditions. Kultti *et al.* (2006) show from macro-fossils that temperatures were 2.5^{o}C warmer than today by *c.* 8500 cal BP. Kultti *et al.* (2006) also quote a Chironomid study by Korhola *et al.* (2002) which found near modern temperatures attained by *c.* 9500 cal BP. These findings suggest that in the eastern Cairngorms, gradually drying climate may have improved conditions for *Pinus* succession from around *c.* 9500 cal BP. Imprecision in dating from Doire Bhraghad mean that these climatic changes may be associated with the increase of *Pinus* at Mar Lodge. The closeness of the increase in *Pinus* percentages at Mar Lodge and Loch Maree suggests that vegetation change at the two sites could be in response to the same climatic changes.

It is possible that regional climatic change affected the whole country, facilitating an increase in *Pinus* percentages. However the demonstration by Froyd (2005) that *Pinus* presence at Loch an Amair from *c.* 9900 cal BP, and at Loch Ness from *c.* 9600 cal BP, did not lead to a rise in *Pinus* percentages at *c.* 9200 cal BP, suggests that drying climate was not the sole cause of increases in *Pinus* abundance. If drying climate was the only factor leading to the increase in abundance of *Pinus* all over Scotland, it seems likely that increases in pollen percentage would have been recorded at both Dubh Lochan and Loch an Amair from the same time as Loch Maree, *c.* 9200 cal BP.

Reference to Table 7.1 and Section 7.4.2 also suggests that regional drying of the climate was not the only factor leading to *Pinus* expansion as the first rise in *Pinus* percentages is from Loch Maree, in northwest Scotland. A pattern might be defined from Froyd's (2005) and Davies' (2003a) sites in Glen Affric. The increase in *Pinus* percentages occurred first, at *c.* 8800 cal BP, on the site nearest to the coast, Dubh Lochan on the eastern side of Loch Ness. The increase in percentages at Loch an Amair was delayed until *c.* 8400 cal BP (Froyd 2005), with the latest rise at Torran Beithe (Davies 2003a), located furthest up the valley of Glen Affric. These dates show migration of *Pinus* from the mouth to the head of Glen Affric, as has to be the case, without describing where *Pinus* actually originated. The Loch Ness population provides a proven population, but the later first record of *Pinus* stomata at Dubh Lochan suggests that *Pinus* in Glen Affric arrived via Strath Glass, directly from the north. This still leaves open the question of whether the ultimate origin was from the North Sea or the Loch Maree area.

The rise of *Pinus* percentages in Speyside, which precede increases in Glen Affric, also fits the model of migration from the northwest. Migration may have been facilitated by the relatively wide valleys leading to Speyside from either an eastward moving population from northwest Scotland or a westward moving population from the North Sea. The increase of *Pinus* in the Howe of Cromar (Edwards 1978) is later than at most other sites, making migration from east or west still feasible. Mar Lodge is perhaps the least accessible of all the locations that have been studied, 30km or so up the narrow Dee valley, yet has one of the earliest first appearances and earliest dates for increases in *Pinus* pollen percentage. This points to a different origin for the Mar and Loch Maree pines with migration of pines in Mar more likely to be from the east than from the west. However if

Pinus in Deeside migrated to the area from elsewhere, increases of *Pinus* pollen percentages in upper Deeside should follow, not lead, increases in mid-Deeside. The early increase of *Pinus* has implications for the source of *Pinus* in the Holocene of Deeside, which are explored in Section 7.5.2.

Summary

At the Doire Bhraghad site the time gap between the first locally occurring *Pinus* individuals and the increase in pollen percentages, indicative of increased local abundance of *Pinus* in the woodland assemblage was *c.* 400 cal years. This equates to two separate episodes of colonisation by *Pinus*, rather than a single viable succession and it is possible that conditions in the *Betula*-*Salix* woodland prevented a more rapid increase in the abundance of *Pinus*. The increase of *Pinus* percentages at *c.* 9200 cal BP is thought to indicate the increased abundance of *Pinus* in the landscape which is correlated with the change to drier conditions identified in Scotland and Fenno-Scandia. An untested hypothesis is that pioneering seedlings were at a competitive disadvantage in substrates lacking appropriate mycorrhizal inoculation.

Pinus initially replaced *Corylus* and *Salix* in the pollen assemblages at Mar Lodge, while *Betula* remained important. *Corylus* was probably displaced from the local vegetation before *Salix*, as *Pinus* occupied the canopy openings favoured by *Corylus*. *Pinus* was able to shade out *Corylus*, and may have disappeared it from the local area within *c.*100-200 cal years. *Salix* was also displaced from the basin vegetation within *c.* 100-200 cal years, but probably remained within the local vegetation assemblage. *Betula* was displaced more gradually, becoming locally absent by *c.* 8600 cal BP. The changes in the woodland assemblage are similar to changes that took place elsewhere in Scotland as *Pinus* became a woodland dominant. The transition from *Betula* woodland to *Pinus* woodland in Mar Lodge occurred earlier than anywhere in Scotland apart from northwest Scotland around Loch Maree. There are complex ecological factors behind the increase of *Pinus* in both Doire Bhraghad and Scotland as a whole, with implication for the origin of *Pinus* particularly in upper Deeside.

7.5.2 Origin of the Mar Lodge pines

In Section 7.4.1, 7.4.2 and 7.5.1 evidence for the first appearance of *Pinus* and the increased abundance of *Pinus* at Mar Lodge, before most other places in Scotland, was set out. Mar Lodge has the second oldest first appearance from stomatal evidence and also the second oldest expansion of woodland from increases in pollen percentage (Table 7.1).

Early first appearances in Glen Affric and Glen Lui require different source populations or almost instantaneous movement of *Pinus* from west to east Scotland. However, the chance colonisation of both areas is possible from the same population. In Section 2.2, it was noted that Birks (1989) details the possibility of 'jump dispersal' involving distances of up to 100km. This becomes more difficult to sustain when seed dispersal paths involve mountain barriers rather than open sea, but is still possible. However, almost simultaneous increases in *Pinus* pollen percentage at Doire Bhraghad and Loch Maree lower the likelihood of a shared population origin. A simpler, and so preferable explanation, is that *Pinus* in Mar Lodge derives from a separate population to *Pinus* in Loch Maree. This is in agreement with the model of genetically distinct east and west populations in Scotland (Kinloch *et al.* 1986) and the view of Sinclair *et al.* (1998) that genetic variation can distinguish populations in western Scotland from those elsewhere.

Significant increases of *Pinus* pollen at Doire Bhraghad occur slightly later than Bennett's (1998) estimate of regional *Pinus* increase but considerably before Edwards'

(1978) expansion of *Pinus* from *c.* 8000 cal BP. If *Pinus* at the Howe of Cromar and in Mar Lodge originate from a common eastern source, these dates also present a difficulty to which there seem to be three solutions.

1. Holocene migration of *Pinus* from east to west up Deeside may have been before the start of Edwards' (1978) Howe of Cromar sequences, although Edwards dates the base of his Loch Davan and Braeroddach sequences to before *c.* 11500 cal BP, making this unlikely.
2. *Pinus* in Deeside originates from the same population, a population that survived in Upper Deeside throughout the Loch Lomond Re-advance. In the Holocene, *Pinus* migrated east and west, arriving at Doire Bhraghad before continuing westward along Glen Dee, Glen Lui and Glen Geldie. If the remnant population was closer to Mar Lodge than to the Howe of Cromar it makes the earlier colonisation of Doire Bhraghad possible, but migration through a landscape virtually devoid of competition is likely to approach the suggested maximum speed of around 800m year-1 (Birks 1989). This makes the late appearance of *Pinus* at the Howe of Cromar, only about 30km from Mar Lodge, less tenable. Nonetheless, favourable conditions for *Pinus* between *c.* 9500 and 9000 cal BP, combined with a more proximal source, may explain the earlier increase in *Pinus* percentage at Mar Lodge.
3. *Pinus* moved past the Howe of Cromar but remained rare and thus did not record large increases in percentages. Edwards (1978) reports that pollen assemblages between *c.* 11500 to 8000 cal BP typically include *Pinus* at up to 9% TLP which in an assemblage dominated by *Betula* could be interpreted as sparse local presence of *Pinus*. Though lacking stomata, assemblages are otherwise not dissimilar to Loch an Amair, Dubh Lochan and Doire Bhraghad. Conditions in the Howe of Cromar were less favourable to *Pinus* than in Mar Lodge, preventing *Pinus* from becoming

locally dominant until later. Conversely a more distal location to the Howe of Cromar meant that chance dispersal did not lead to chance colonisations or early spread of woodland.

The first two scenarios seem very unlikely. It is difficult to envisage conditions preventing eastward movement of *Pinus* to the Howe of Cromar until later in the Holocene. Recent evidence (Everest and Kubik 2006, Section 3.4) showing more limited valley ice during the Loch Lomond Re-advance than was previously envisaged (Sugden 1970) affects only uppermost Glen Dee. Disappearance of ice allows the possibility of vegetation growth in upper Glen Dee during the Loch Lomond Re-advance, but the existence of a viable population of *Pinus,* remaining unrecorded, in a vegetation assemblage dominated by Poaceae and Cyperaceae, with other herbs and *Empetrum* (Edwards 1978, Huntley 1994), is unlikely. For a viable *Pinus* population not to expand rapidly onto the bare ground that was surely a feature of the valley at this time, before the arrival of *Betula* and *Corylus,* seems even less likely.

Scenario three is therefore the most probable explanation of the early expansion of *Pinus* woodland in the Mar Lodge area. The opportunities available to *Pinus* around Doire Bhraghad (Section 7.5.1) were probably not available at the Howe of Cromar, but the River Dee, provided a route-way of relatively disturbed or marginal ground suited to the rapid movement of *Pinus* (Bennett 1984, Birks 1989).

There is no further internal evidence by which to test these alternative scenarios. However, further analysis of the Doire Bhraghad sequence, below the stratigraphic levels already sampled, might reveal the presence of a population of *Pinus* prior to that currently proposed. It must be remembered that absence of stomata during the Loch Lomond Stadial or earlier in the Lateglacial, for example, would not prove the absence of *Pinus* during this time. However the longer the record of stomata extends back into the Holocene the more likely it becomes that a population persisted throughout the Loch Lomond Stadial. The best evidence for any of these scenarios would require analysis of Loch Davan and Braeroddach Loch in the Howe of Cromar for stomata or analysis of other sequences in Upper Deeside. Long peat deposits, perhaps starting before the beginning of the Holocene may be available on the Invercauld and Balmoral Estates. The sites are shown on Figure 3.1, locations 13 and 14, with location 14 being the site of Figure 2.4 and 2.5.

The difference between the beginning of increases in *Pinus* pollen at Loch an Amair and Torran Beithe in Glen Affric, (a mean of *c.* 400 cal years; Sections 2.6.4; 7.5.1), is probably the length of time that *Pinus* took to move between the sites, toward the head of the valley. The basal ages of the sequences at Geldie Lodge and White Bridge means that it is not possible to suggest the time taken for the migration of *Pinus* from Doire Bhraghad further west: all indicators (pollen, stomata, Coleoptera) agree that *Pinus* was firmly established at Geldie Lodge before peat inception at *c.* 7550 cal BP.

There is therefore no current means of showing whether pine at Geldie Lodge migrated eastward from Speyside and Glen Feshie or westward from Deeside. The rise of *Pinus* percentages in Speyside and in Glean Einich, from *c.* 8900 cal BP (O’Sullivan 1974a, 1976, Binney 1997) make migration of *Pinus* from there possible. The height of Moine Mhor at the head of Glean Einich, 900m OD, makes this route very unlikely but the watershed between the Feshie and Geldie rivers is 540m OD (Section 3.2), allowing the possibility of migration of *Pinus* by that route.

Summary

Near simultaneous increases of *Pinus* percentages in Mar Lodge and Loch Maree are in agreement with the model of separate origins for *Pinus* in east and west Scotland. However the increase of *Pinus* percentages in Mar Lodge before increases further east in the Howe of Cromar is problematic as migration of *Pinus* from the east should pass by mid Deeside before arriving in Upper Deeside. The most plausible explanation for this disparity is very rapid movement of *Pinus* along the River Dee, passing through the Howe of Cromar without a large increase in pollen percentages. It is possible, but unlikely, that a population of *Pinus* remained in upper Deeside throughout the Loch Lomond Stadial, this can only be tested from further analyses of other sites. The date of the increase of *Pinus* percentages at Geldie Lodge, like the first arrival of the taxa is unknown. The speed at which *Pinus* moved between Glen Lui and Glen Geldie is also unknown.

7.6 Correlation of Coleopteran and palynological sequences at Geldie Lodge

The sediment at Geldie Lodge was sampled from the same location as Clark's (2003) Coleopteran study specifically to provide dating control for Clark's undated analyses and to allow her data to be used in conjunction with pollen and stomatal analyses (Section 3.3.3). Her data are introduced in later sections but the stratigraphic correlation is explained here.

The two sediment sequences have different thicknesses of peat, and the lack of detail in Clark's (2003) description of the peat stratigraphy makes it difficult to correlate the two sequences with precision. It is possible that the sediment between 82 and 91cm in Clark's study (Figure 3.21) correlates with the heavily humified peat from 50-60cm (Table 6.1). Another clear change is at 40cm (this study) and 50cm (Clark 2003) when the proportion of identifiable plant material increases in both sequences. The location of woody material is probably key to establishing correlations. Assuming the position of the top of Clark's (2003) stump layer is accurately portrayed at 75cm, a correlation between that and the last wood fragments in this study at 91cm seems acceptable.

The basal date of the pollen sequence, *c.* 7550 cal BP, allows an approximate timescale to be provided for Clark's (2003) undated study. Clark's Coleopteran Phase 1 (100-129cm) is from *c.* 7000 to 7600 cal BP, approximately equivalent to lpaz GL1. Coleopteran Phase 2 (75-100cm) is roughly equivalent to lpaz GL2 and the base of lpaz GL3, *c.* 5400 to 7000 cal BP, with Coleopteran Phase 3 (0-75cm) corresponding to the remainder of the pollen sequence. Clark's sub-samples are taken at 5cm intervals, meaning temporal resolution of the sequence declines through the sequence. During Clark's Phase 1 each of the six samples average nearly 100 cal years of peat accumulation, increasing to an average of over 320 cal years in the five sub-samples of Phase 2 and an average of *c.* 360 cal years in Phase 3.

7.7 Diversity of the Holocene woodland assemblage in Mar Lodge and Scotland

There have been only three canopy forming taxa present in the vegetation of the Mar Lodge sites in the Holocene, *Betula*, *Pinus* and *Corylus*, with only *Betula* and *Pinus* definitely locally present at all three sites. Furthermore *Betula* percentages are variable and are low enough to be considered absent from the local area of all three sites for extended periods. At Doire Bhraghad *Betula* is probably locally absent from *c.* 7700 cal BP onwards, while at Geldie Lodge *Betula* may be present until *c.* 1500 cal BP. Local presence of *Betula* is likely at White Bridge only between *c.* 2800 and 1900 cal BP.

For a large portion of the Holocene (*c.* 9200 cal BP onwards) *Pinus* was the dominant and probably sole arboreal taxon present in the local vegetation at Doire Bhraghad. From *c.* 7550 to 3000 cal BP, *Pinus* usually dominated the pollen assemblage at Geldie Lodge but *Betula* was usually present. *Pinus* at White Bridge also typically dominated the assemblage from peat inception to *c.* 1900 cal BP, with *Betula* only a minor presence.

Altitudinal differences probably contributed to the differences in *Betula* representation between sites at Mar Lodge, particularly its greater importance at Geldie Lodge. Sustained presence of *Betula* at Geldie Lodge as part of a *Pinus-Betula* woodland is in agreement with deciduous woodland Coleoptera identified by Clark (2003) from *c.* 7550 cal BP. A relatively dense *Betula-Pinus* canopy with a heath understory here is comparable with the plant communities at the same altitude in Gleann Einich (Binney 1997) and the continued importance of *Betula* links the assemblages at Geldie Lodge with that at Allt A'Phris-Ghiubhais. Though the higher sites of Carn a'Phris Ghiubhais (630m OD) and Lochan Odhar (740m OD) had a dense *Pinus* canopy by *c.* 7500 cal BP, subsequently all four sites had variations in canopy density with *Betula* remaining part of the woodland assemblage. Change in the dominant species and also greater proportions of non-arboreal taxa link these assemblages.

Uncertainties in establishing the presence of *Corylus* at Doire Bhraghad have already been considered (Section 7.3). Initially *Corylus* percentages (Section 4.5 lpaz DB1) are high enough to indicate local presence (Huntley and Birks 1983, Birks 1989) but declines in percentage after *c.* 9100 cal BP suggest local disappearance. At White Bridge, *Corylus* percentages are never higher than about 2% TLP, even during phases of open canopy. This is in agreement not only with local absence, but also extra-local absence.

Corylus may have been locally present at Geldie Lodge. Percentages consistently exceed 5% TLP between *c.* 7338 and 6700 cal BP and sporadically at other times in the sequence. *Corylus* may have continued to be locally present at Geldie Lodge until as late as *c.* 2260 cal BP, but is unlikely to have been present after *c.* 4000 cal BP. Although it is likely that *Corylus* was present for similar periods at Geldie Lodge, White Bridge and

Doire Bhraghad, the extended period of sporadic higher percentages of *Corylus* at Geldie Lodge may indicate extended local presence, perhaps indicative of the preference of *Corylus* to the more open plant communities around Geldie Lodge. A more constant presence of *Corylus* here may also be an indication that, though higher, the wide valley at Geldie Lodge was less prone to damaging frosts than Doire Bhraghad or White Bridge.

Salix was locally present in lpaz DB1, but probably disappeared after *c.* 9100 cal BP and was not present after *c.* 5800 cal BP. *Salix* may have been present at White Bridge, but very low percentages even during open-canopy phases make this unlikely. At Geldie Lodge *Salix* percentages are slightly higher than at White Bridge, and more consistently present before *c.* 5850 cal BP; local presence after this is unlikely. This is in agreement with the appearance, in Clark's (2003) Coleopteran assemblage, of *Quedius semiaeneus* (Steph.), a *Salix* indicator, between *c.* 7000 and 6500 cal BP (90 to 95cm). *Sorbus* may have been present, occasionally and at very low abundance, at almost any point in the Doire Bhraghad sequence, but was absent from both other sites.

The three other arboreal taxa commonly appearing in the Mar Lodge pollen assemblages, *Alnus*, *Quercus* and *Ulmus* are not likely to have been locally present in the vegetation assemblage at any of the three sites.

Individual *Alnus* trees could have survived at all three of the Mar Lodge sites. However with the possible exception of examples high in the Campsie Fells (Dickson 1988), there are no examples of *Alnus* being found naturally at even the height of Doire Bhraghad, around 100m above its modern altitudinal limit. Catkin production is particularly affected by wind strength (McVean 1955a), which may mean *Alnus* is especially ill-suited to the open high valleys of Geldie Lodge and White Bridge. Without catkin production, *Alnus* would be palynologically invisible. This makes temperature changes during the Holocene less relevant to *Alnus*.

Wind strength, also an important agent of disturbance (Quine 2003, Tipping 2008), varied during the Holocene affecting the formation and form of woodland. Gilbertson *et al.* (1999) suggest a chronology for storminess for the Outer Hebrides based on periods of increased sand drift. *Alnus* pollen frequencies at the comparatively high altitude and exposed Mar Lodge sites might be expected to increase in periods of reduced storminess but in general there is no correlation. Slight increases in the percentage and concentration of *Alnus* may be associated with low storminess between *c.* 6000 and 5500 cal BP at Geldie Lodge and from *c.* 3300 to 2300 cal BP at White Bridge, but increases in *Alnus* percentages are often more associated with periods of higher sand drift, between *c.* 4800 and 2900 cal BP spanning two periods of increased *Alnus* percentage at Doire Bhraghad, and from *c.* 5800 to 4200 and 3800 to 3300 cal BP. This pattern is probably more indicative of increased long distance influx as wind strength periodically increased.

Quercus is limited to an altitude of around 450m OD (Grime *et al.* 2007) and is therefore a possible component of Doire Bhraghad and White Bridge assemblages. The finding by Shaw (2006) that 10% TLP indicates local presence is at odds with Huntley and Birks' (1983) much lower 2% TLP. At Doire Bhraghad *Quercus* values are between 5 and 10% TLP from *c.* 3800 to 3200 cal BP, during a phase of opening canopy, making long distance influx perhaps a more likely explanation. *Quercus* at Geldie Lodge exceeds 5% TLP between *c.* 4800 and 4000 cal BP and at *c.* 6400 cal BP. To have been present at Geldie Lodge, *Quercus* would have to have been definitively present at White Bridge or Doire Bhraghad, but it is not. Migration up Glen Feshie or Glen Tilt would certainly be unfeasible. Slightly higher percentages are therefore products of long distance pollen input.

The altitudinal limit of *Quercus* may be set by the effects of frost. The impact of frost may have affected *Corylus*, but flowering of *Quercus* is also detrimentally affected, particularly late spring frosts (Grime *et al.* 2007). Furthermore, acorns are susceptible to frost damage. This combination of factors may have prevented the movement of *Quercus* to its altitudinal limit of 450m. *Quercus* is unlikely to have been present locally at any of the Mar Lodge sites, but values of more than 5% TLP at Geldie Lodge and Doire Bhraghad probably indicate movement west of Edwards' (1978) Howe of Cromar sites.

Ulmus is potentially to be found up to 540m, but no saplings are recorded above 300m (Grime *et al.* 2007). Presence at Mar Lodge is made less likely with reference to Shaw's (2006) finding that local populations of *Ulmus* produce large amounts of pollen. Low percentages in the Mar Lodge sequences make local presence extremely unlikely. The highest percentages, 5- 8% TLP, are found at Geldie Lodge between *c.* 6700 and 5700 cal BP. This may indicate pollen transport from the west, e.g. Glen Feshie, rather than from a source to the east in lower Deeside.

Ground floral diversity is similar at all three sites, though the proportions of non-arboreal taxa are different. At Doire Bhraghad non-arboreal taxa typically comprise less than 25% TLP between *c.* 2000 until 9200 cal BP. Prior to *c.* 2000-2500 cal BP Poaceae was dominant but dwarf shrubs only became important after *c.* 2000 cal BP. Dwarf shrubs dominated the assemblage at Geldie Lodge after *c.* 2500 cal BP.

The paucity of tree and shrub taxa in the Mar Lodge vegetation is in contrast to most core areas of *Pinus* especially in the early to mid Holocene. At Loch Pityoulish (O'Sullivan 1976) *Betula* remained in the vegetation assemblage throughout the Holocene, and after *c.* 3500 cal BP began to replace *Pinus*. *Alnus* also became important after this date. *Betula*, *Alnus* and *Populus* were relatively important at Loch Garten, together with *Corylus* (O'Sullivan 1974a). In Abernethy forest, *Betula* and *Alnus* were important in the woodland assemblage with *Pinus*, until after *c.* 4260 cal BP (Pratt 2006a).

The Loch Maree vegetation assemblage included *Quercus* and *Alnus*, in addition to *Pinus* and *Betula*. Woodland at the western end of Glen Affric was equally diverse, including *Pinus*, *Betula*, *Sorbus* and *Populus* (Davies 2003a). *Betula* remained important as *Sorbus* and *Populus* declined but more nutrient demanding taxa, *Fraxinus, Quercus, Ulmus* and *Corylus* were present by *c.* 7220 cal BP (Davies 2003a). Taxa found by Davies (2003a) are also found locally by Shaw (2006), at several sites in east Glen Affric until the late Holocene. Tree and shrub taxa at Loch an Amair were as diverse as other sites in Glen Affric (Froyd and Bennett 2006).

Continued importance of *Betula* in pollen assemblages at peripheral sites such as Loch Sionascaig (Pennington *et al.* 1972), Beinn Dearg and Gleann Einich (Binney 1997) and on Rannoch Moor (Ward *et al.* 1991) suggests an affinity with the Geldie Lodge assemblage. In the case of some higher altitude sites, high *Betula* percentages may be indicative of the proximity of the treeline. However, at the sites mentioned, high *Betula* percentages indicate the presence of *Betula* in the local vegetation assemblage.

The absence of a more diverse arboreal assemblage in Mar Lodge was probably due to a combination of location, altitude and climate. It is likely that, like *Pinus,* all arboreal taxa migrated into upper Deeside along the long narrow Dee valley (Section 7.5.1). The low arboreal diversity of upper Deeside may reflect the difficulty of plant migration up a valley essentially isolated from the rest of Scotland; Doire Bhraghad is around 30km from the mouth of the valley and Geldie Lodge is a further 10km west. As northward movement of *Quercus* was slowed by the effects of the Grampian Mountains (Birks 1989, Tipping 1994), presumably movement up a relatively narrow valley would also have been slow.

The climatic conditions of the eastern Cairngorms, especially strong winds and late cold springs, are exacerbated by the relatively high altitude even of Doire Bhraghad. Glen Lui may be more sheltered than Glen Geldie, but its position below Beinn MacDuibh and Beinn a'Bhuird probably results in regular temperature inversions, as cold air drains off the plateaux. This may also help explain the possible sporadic local presence of *Corylus* at

Geldie Lodge throughout the Holocene, as *Corylus* may have been better able to flower due to slightly less intense frost. It is also possible that *Corylus* was more able to compete with the less dense *Pinus-Betula* canopy at Geldie Lodge.

That *Pinus* retained greater importance in Mar Lodge compared to other areas because of the absence of arboreal competition seems self evident. *Corylus* and *Sorbus* may have been shaded out by *Pinus* but *Betula* was still present, competing for canopy gaps. However the absence of *Alnus* and *Quercus* meant that competition on waterlogged or infertile sites was greatly reduced. It seems likely that *Alnus* and *Ulmus* could not have survived at Mar Lodge even in the absence of *Pinus,* and that *Quercus* would have been on the boundary of its ecological tolerance. It was not the case that these taxa were ousted or prevented from growing in Mar Lodge by competition from *Pinus*, but that *Pinus'* tolerance of the climate in Mar Lodge allowed it to grow on substrates from which other taxa would exclude it at lower altitudes. Lack of competition at Geldie Lodge may have allowed *Pinus* to grow in conditions from which it would normally be excluded e.g. by *Alnus*.

Rarefaction analysis at Doire Bhraghad shows that palynological richness varies from 37 to 19; highest in the early Holocene. Palynological richness at Geldie Lodge and White Bridge is similar, giving values between 37 and 26 and 39 and 26 respectively, but with no directional trend evident. Shaw (2006) and Froyd and Bennett (2006) also calculated palynological richness for their assemblages, finding values of between 27 and 11 (Shaw 2006) and 20 and 12 (Froyd and Bennett 2006). Froyd and Bennett (2006) report that palynological richness is higher at the beginning of the Holocene, while Shaw's sites do not extend back to the early Holocene.

Differences in palynological richness at Mar Lodge and Loch An Amair may reflect differences in pollen recruitment. Lake sediments are more likely than peat deposits to derive a greater proportion of pollen from extra-local and regional sources, diminishing the importance of rare types of pollen. The difference may also be statistical. The normalised figure of 250 grains from Loch an Amair is considerably lower than the normalised figures used in Mar Lodge, Doire Bhraghad 502, Geldie Lodge 499 and White Bridge 450. However the normalised figures used by Shaw (2006) between 430 and 504, gave palynological richness values of between 27 and 11, comparable to Loch an Amair. Values from Glen Affric seem to be similar from both lake and peat deposits, suggesting there was genuinely higher palynological richness at Mar Lodge.

Higher palynological richness at the Mar Lodge sites may be attributable to a more diverse field and ground layer, particularly heath taxa, but it must be remembered that a high value does not necessarily mean that the vegetation assemblages in Mar Lodge are more diverse. All rarefaction analyses follow the technique of Birks and Line (1992), and exclude taxa comprising less than 2% TLP from the calculation. Higher palynological richness may indicate that overall the canopy was more open than in Glen Affric, allowing greater input of pollen derived from extra-local or regional sources.

Summary

The arboreal assemblages in the Mar Lodge sites were not as diverse as in many other core areas of *Pinus* woodland in Scotland. Only *Betula* and *Pinus* were locally present at all three sites though *Corylus* and *Salix* were sporadically present at Doire Bhraghad and Geldie Lodge, especially before *c.* 5800 cal BP. *Pinus* typically dominated assemblages and, especially at Doire Bhraghad and White Bridge was also often the only arboreal taxon locally present. At Doire Bhraghad *Pinus* was the dominant arboreal taxon from *c.* 9200 cal BP onwards, while in the much younger White Bridge sequence *Pinus* was the dominant and probably sole taxon for most of the period in which it was locally extant. *Betula* was possibly a minor constituent of the White Bridge vegetation assemblage from *c.* 2800 to

1900 cal BP. At Geldie Lodge the arboreal assemblage generally consists of *Pinus* and *Betula* until *c.* 3000 cal BP, and *Betula* remains present throughout the period of extant woodland. *Sorbus* may also have been locally present at Doire Bhraghad, but did not appear in either of the other sites.

Differences between arboreal assemblages at Doire Bhraghad and Geldie Lodge were probably due to the difference in altitude between the sites. There are no differences between the constituents of the ground flora; differences in the proportions of the arboreal to non-arboreal taxa mainly reflect differences in the canopy and altitude.

The rather low diversity of the Mar Lodge assemblages is in contrast to other areas of core *Pinus* woodland, where *Alnus, Fraxinus*, *Quercus*, *Populus, Sorbus* and *Ulmus* can be found. It is suggested that low diversity in Mar Lodge results from a combination of the relatively high altitude, the local climate and the isolated nature of the Upper Deeside. Though diversity was low in the Scottish context, absence of *Corylus*, for example, may be typical of this part of the Cairngorms. Low arboreal diversity, and therefore more limited competition may have allowed *Pinus* to have been more dominant in upper Deeside than elsewhere in Scotland.

Comparison of palynological richness with Glen Affric, the only other area for which rarefaction analyses are available, shows the diversity of the pollen assemblage to be greater in Mar Lodge than in Glen Affric. This does not necessarily translate into more diverse vegetation assemblages. It may simply reflect greater extra-local or regional pollen influx as a result of a more open woodland canopy.

7.8 Visual appearance of trees

In Section 2.6.8 it was noted that pollen evidence provides little or no evidence regarding the appearance of individual trees. However, at Geldie Lodge this may be possible with reference to Clark's (2003) Coleopteran study. There are taxa indicating the presence of woodland from the base of Clark's sequence, with *Pinus*-specific indicators from the second sub-sample at *c.* 7450 cal BP. Each of the seven sub-samples between *c.* 7370 and 5740 cal BP has at least one record of a suite of saproxylic *Pinus* indicators, suggesting tree growth under stress (Clark 2003). Furthermore at *c.* 6050 to 5700 cal BP (80-85cm) Clark (2003) identified *Pityogenes quadridens* (Hartig), a beetle that breeds in thin-barked *Pinus*. Clark (2003) quotes Agee (1998) in concluding that this indicates *Pinus* individuals under about 50 years old. This suggests that at the equivalent level in the pollen diagram, lpaz GL3, at least some trees resembled individuals shown in Figure 2.3, small, with a poorly developed canopy.

At Geldie Lodge it seems likely that the presence of *P. quadridens* and other saproxylic Coleopteran species are indicative of a form of *Pinus* growth that may have represented normal growth at this location. The pollen record from *c.* 6050 to 5450 cal BP shows *Pinus* to have been declining: percentages are low, and stomata are absent for *c.* 600 cal years. In Section 6.5 (lpaz GL3), this was interpreted as a decline in the local presence of *Pinus*, including disappearance from the core site, linked to an increase in mire surface wetness (from *Sphagnum* percentages, Section 6.5 lpaz GL3). An unchanged Coleopteran assemblage, including *Pinus*-specific saproxylic Coleoptera, before, during and after the oscillation in pollen suggests that there is limited change to the growth form and location of *Pinus*.

This period of 600 or more cal years represents at least two generations of trees but for stressed trees many more generations are likely in this time span. Despite the similar Coleopteran assemblage, the temporal acuity of Clark's (2003) sequence is such that there is considerable scope for growth form and location to change within this time, but there does not seem to be any reason for a change in growth form, e.g. to *krummholz* form.

Bridge *et al.* (1990) report relatively short-lived trees (70% with less than 125 years of growth) on Rannoch Moor, during the period of viable *Pinus* growth on the mire between *c.* 7250 and 4600 cal BP. Moir *et al.* (2010) also report relatively low average ages (20% average under 100 cal years and 60% under 150 cal years) for sub-fossil stumps preserved in peat in northern Scotland. Probable conditions at Geldie Lodge would suggest that colonisation of the mire surface was by short-lived, small trees throughout the period.

A second, larger increase in *Sphagnum* spores between *c.* 4870 and 4220 cal BP, casts doubt on whether increasing mire surface wetness always causes a *Pinus* decline, as it occurs during a phase when percentages of *Pinus* increase and stomata reappear. At this time the saproxylic *Pinus* indicator *Ampedus nigrinus* (Hbst) is identified in the Coleopteran assemblage, again suggesting sub-optimal growth conditions for *Pinus* trees, with short-lived trees resembling those described above and in Figure 2.3.

The greater importance of field layer taxa at Geldie Lodge is in agreement with the lighter canopy associated with shorter-lived, smaller trees. Conversely the lesser importance of taxa in the field layer at Doire Bhraghad between *c.* 4800 and 9200 cal BP may be indicative of larger, more long-lived trees with a larger spreading canopy. The presence of at least some thin-barked trees at Geldie Lodge suggests that for extended periods in the Holocene, trees growing directly over the core site on the mire surface were short-lived small individuals. However it is possible that not all trees in the local area looked identical. There may have been trees growing in the local area, away from the mire, of the same form as at Doire Bhraghad today.

Two of Binney's (1997) three high altitude sites in Gleann Einich show an opening canopy between *c.* 5700 and 6300 cal BP and *Pinus* abundance at Farlary (Tipping *et al.* 2008) also changed. At Farlary *Pinus* pollen decreases but stomatal counts remain high, which is interpreted as continued local presence, as extra-local or regional *Pinus* populations declined. Tipping *et al.* (2008) also regard this period as one of increasing mire surface wetness. At their low altitude site this leads to competition from *Alnus* and other deciduous taxa, including *Betula*, neither of which occurs at Geldie Lodge.

7.9 Visual appearance of woodland

It is likely that woodland in the early or even mid-Holocene will have been significantly different in appearance to modern woodland, as pressures on vegetation changed. The appearance of this early to mid-Holocene woodland is the now lost woodland of interest to archaeologists (Austin 2000). In this section the visual appearance of this woodland is reconstructed from the local arboreal taxa. The abundance and types of these will have affected the canopy density, which in turn has an effect on the non-arboreal assemblage. Non-arboreal taxa have been suggested as driving composition of the canopy (Nilsson and Wardle 2005), but only in special circumstances. Composition of the field layer often provides information corroborating inferences of change in the canopy. There are further inferences from Clark's (2003) Coleopteran assemblages. A summary comparison of changing canopy density is presented in Figure 7.2.

At Doire Bhraghad *Pinus* percentage and influx data suggest a dense canopy consisting solely of *Pinus*, from *c.* 9150 until 4800 cal BP, with tree growth directly over the mire surface until *c.* 5800 cal BP. Proportions of many non-arboreal taxa remain low throughout this period. Low concentration and influx values of some heath taxa, including *Vaccinium* and *Calluna*, suggest these plants were genuinely sparse but the abundance of all heath taxa may be greater than they appear if *Pinus* pollen production is high enough to overwhelm pollen production by all other taxa. Higher concentrations and influx of Poaceae suggest it to have been more abundant.

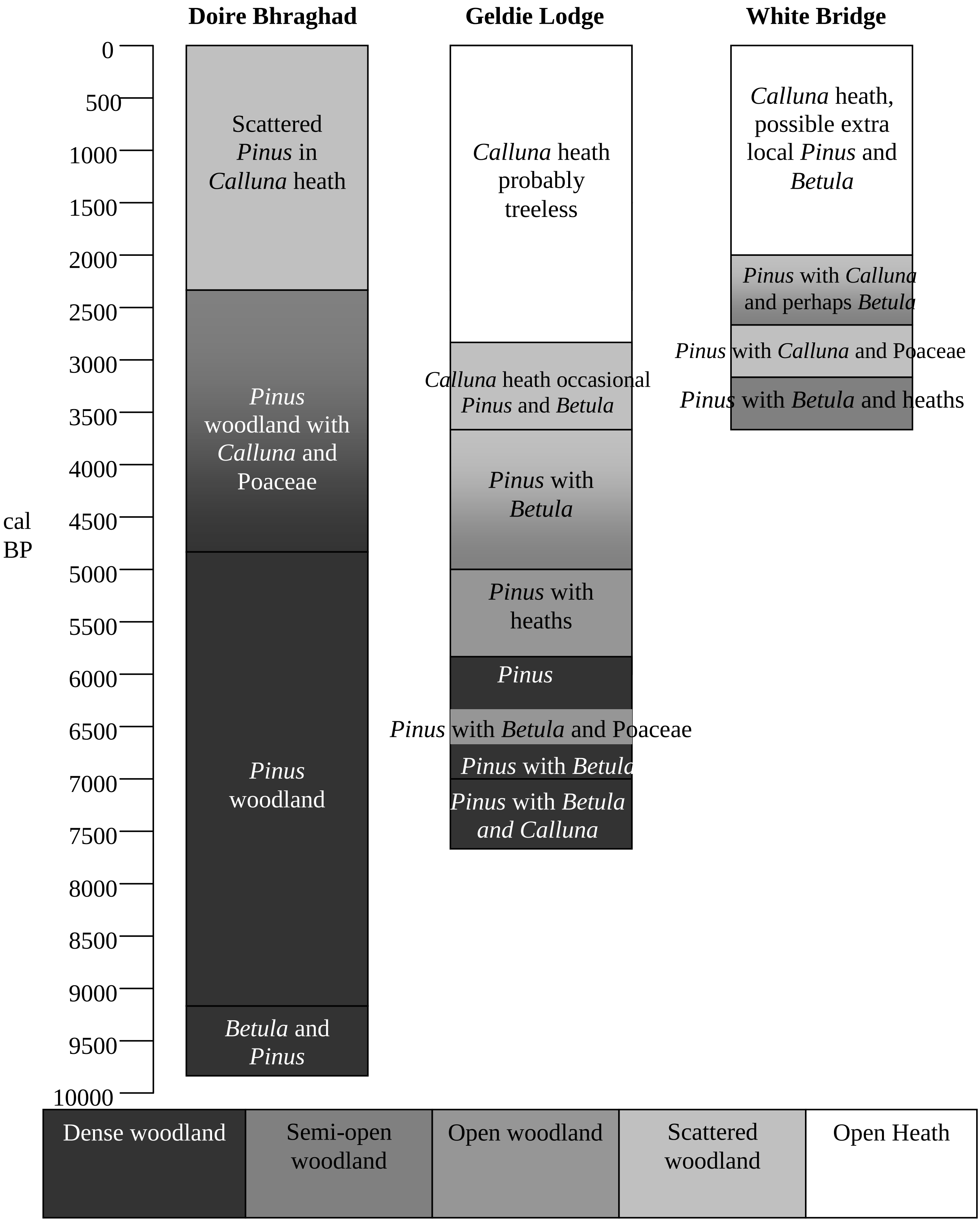


Figure 7.2 Summary comparison of woodland in Mar Lodge Estate

Figure 7.3 Variation of ground flora under open *Pinus* wood in Glen Quoich. Under denser canopy, for example in the left foreground, *Vaccinium* is predominant, while *Calluna* is typically more important in more open patches along with Poaceae, (centre). It is likely that in the past such variation was also typical of ground flora under the pine canopy. In modern woodlands very closely spaced trees (trunks about 1m apart) reduce ground flora to mosses with very little grass and occasional *Vaccinium*.

The pollen assemblage at Doire Bhraghad is suggestive of a mosaic of plant communities in the field layer, dominated by Poaceae, with dwarf shrubs in less shaded parts of the woodland. A mosaic ground flora is a common feature in the modern woodlands of Glen Quoich and Glen Derry, though now it usually involves *Vaccinium* in the shaded parts of the woodland and *Calluna* in the more open sections (Figure 7.3). Nonetheless, this suggests that though dense, the canopy around Doire Bhraghad was not closed. This may have been particularly true of the basin at Doire Bhraghad.

Unlike the assemblage at Doire Bhraghad, the pollen assemblage at Geldie Lodge is not indicative of a long period of stable woodland. Fluctuations in arboreal pollen percentage and influx suggest almost constant change to the canopy, suggesting that a vegetation mosaic was more pronounced for arboreal and non-arboreal taxa. From peat inception the woodland assemblage included both *Betula* and *Pinus*, emphasising the difference in the character of the woodland at Geldie Lodge compared to Doire Bhraghad. The field layer had a much greater proportion of heath taxa and, except for a short period, *c.* 6400-6660 cal BP, a lower proportion of Poaceae. The unstable nature of the woodland assemblage means that defining a date when canopy fragmentation began is not so relevant at Geldie Lodge; both *Betula* and *Pinus* remained locally present until *c.* 3000 cal BP. However during the final phase of woodland, from *c.* 4800-3000 cal BP, the canopy was more open than before.

Though indicative of the local presence of both taxa, pollen percentage and influx of *Betula* and *Pinus* are variable. Influx is especially variable, with a series of short peaks that do not always correlate with changes in percentage. These peaks could relate to variations in pollen production, that is, mast years, as a direct result of the more marginal environment (Section 2.2, Section 7.8), or short-lived changes in rates of peat accumulation not defined by the available radiocarbon assays. The length of time between samples, *c.* 50-

100 cal years, and the 15-20 cal years of peat accumulation within each sample (Table 6.3), casts doubt on the first interpretation. It is more tenable to regard variable influx as an aspect of more open, more marginal woodland. At Geldie Lodge variable influx is probably indicative of changing numbers of shorter-lived trees.

Variation in percentage and influx thus show change to the woodland assemblage, with *Pinus* being particularly important around *c.* 7550 cal BP, from *c.* 7300 to 6760, 6400 to 5900 and 5000 to 4800 cal BP. Other periods shown as dense woodland in Figure 7.2 occurred during phases when *Betula* was a more important component of the canopy. Stomata are usually present when the percentage and influx of *Pinus* are high, the exception being from *c.* 6660 to 6400 cal BP, where despite the low influx and relatively low percentage values, stomata indicate that *Pinus* was still locally present.

The higher percentage of heath taxa throughout the sequence is in agreement with a consistently semi-open canopy, and with the greater importance of a less dense *Betula* component in the canopy. High Poaceae percentages (*c.* 6650 to 6450 cal BP) also show that breaks in the canopy are as likely to lead to increases in non-arboreal taxa as *Betula*. The vegetation at Geldie Lodge was probably a rather more complex mosaic than at Doire Bhraghad, with temporal and spatial variation in the canopy and on the ground. Inferences made in Section 7.8 suggest that larger, longer-lived *Pinus* individuals were present locally, probably growing away from the mire surface. Possible sites include the series of solid parallel ridges to the west of the core site (Section 3.3.3). The site of Geldie Lodge itself (the actual building) is well above the level of the modern mire and it is likely that the promontory has always been beyond the extent of the mire. Existence of such longer-lived individuals on sites peripheral to the mire could have served as a constant source of viable seeds maintaining the mire population.

Figure 7.4 Open *Pinus-Betula* woodland, Flanders Moss, Stirling, provides a possible analogue of the appearance of woodland at Geldie Lodge. Mature trees are widely spaced in this image but great efforts have been made to ‘preserve’ the moss by removing *Pinus* saplings. Despite this there are large numbers of saplings of various ages, but also sizeable gaps with no mature trees or saplings, suggesting semi-open woodland could develop.

Vegetation at Geldie Lodge was affected by fire at various points in the Holocene. One clear event, between *c.* 6540 and 6660 cal BP (lpaz GL2, Figure A.3a) overlaps with a large Poaceae peak between *c.* 6450 and 6650 cal BP and Clark (2003) identified Coleopteran species associated with charcoal between *c.* 6360 and 6680 cal BP. These are in agreement with woodland affecting fires for an extended period of time and are further considered in Section 7.12.

Woodland at Geldie Lodge may have resembled the vegetation on the mire shown in Figure 7.4, though this image is from a dissimilar mire in terms of altitude and origin (Flanders Moss near Stirling). The similarities are that there are a few mature trees, both *Betula* and *Pinus*, but a large number of saplings. The much more limited extent of the mire surface and more enclosed valley at Geldie Lodge, suggests closer proximity of mature *Pinus* and *Betula* trees, giving a denser canopy, but a similar ground flora.

A vegetation mosaic also typified the local area at White Bridge. In this case, it is likely to have consisted of larger, long-lived trees growing on the dry terrace to the north of the core site, and perhaps on the area to the south of the mire. *Pinus* may have grown on the mire surface itself, but it is possible that the palaeochannel remained treeless throughout the sequence. Disagreements between *Pinus* percentage and influx, such as the boundary between lpaz WB1a and 1b, *c.* 3320 cal BP and lpaz WB2a and 2b, *c.* 2760 cal BP may arise as a result of an insufficiently robust chronology but it may also relate to the sharp spatial differentiation of substrates at White Bridge (Section 5.5). The pollen assemblages include values of *Betula* indicative of local presence, though this local presence may relate to trees on the valley sides (Section 5.5), leaving the valley floor exclusively occupied by *Pinus*. The consistent percentage of dwarf shrubs indicates that heaths dominated the field layer, with Poaceae less important.

During the short woodland phase at White Bridge (*c.* 3500 to 1900 cal BP), *Pinus* pollen percentages and influx are variable. This period of the White Bridge sequence has the shortest sampling interval, just over 30 years, of any of the Mar Lodge sites. An interval of *c*. 30 years is still too long to reveal annual changes in pollen production and though it seems short for major changes in canopy density, the gradual change between peaks makes them unlikely to relate to phenomena such as mast years. The White Bridge sequence commences after woodland began to fragment at Doire Bhraghad, suggesting that the variation in pollen percentages and influx are related to fragmentation of woodland at White Bridge.

As already discussed (Sections 2.6.7 and 7.7) there is nowhere else in Scotland that has a woodland history in which *Pinus* was so dominant. As a result of this unusual predominance, the woodlands of Glen Lui and Glen Dee may have always appeared visually different to those of Loch Maree, Glen Affric and Speyside. Birks (1972) does not attempt to describe the form of the woodland at Loch Maree, but in Abernethy Forest she regards *Betula* and *Populus* as occupying canopy gaps and open situations (Section 2.6.8) forming a woodland mosaic. None of the analyses (Birks 1970, O'Sullivan 1974a and 1976, Birks and Mathewes 1978) report *Pinus* percentages higher than 60%, and all regard *Betula* as having an important continued presence in the early Holocene.

Pratt (2006a) reports *Pinus* percentages of more than 80% TLP substantially before *c.* 4260 cal BP from Tore Hill (East Abernethy Forest). However Pratt (2006a) also reports that the integrity of this sequence is questionable, as none of her other sequences have *Pinus* percentages of greater than about 60% TLP. O'Sullivan (1974a, 1976) and Birks and Mathewes (1978) describe the understorey of the *Pinus* with *Betula* woodlands as initially dominated by dwarf shrubs with Poaceae only becoming important later in the Holocene.

Froyd's (2005) assemblages also indicate a *Pinus-Betula* assemblage throughout the Holocene at Loch an Amair and Dubh Lochan. Davies (2003a) regards the *Betula-Pinus* canopy as being broken by mire communities. This is, by definition, also the case for all three sites at Mar Lodge, if only because each is taken from a mire. The nature of the landscape in Glen Lui suggests that Doire Bhraghad was typically a less open woodland than many other core areas; but in both Glen Lui and Glen Dee, openings within the canopy would have been provided by the rivers. Whether the riverbanks formed a break to the *Pinus* canopy is uncertain as they are outside the RSAP for both Doire Bhraghad and White Bridge. At Geldie Lodge the Geldie Burn is within the RSAP and open woodland is more apparent.

Summary

Measures of canopy density are generally in agreement with each other. *Pinus* pollen percentage and influx, AP/NAP ratio and *Empetrum* percentage data do not always all indicate the same canopy density but usually only one of the four measures employed disagrees with the others. Together they suggest that Doire Bhraghad consisted of a canopy of solely *Pinus* woodland denser than most other areas of Scotland, and that the woodland survived with little change until the late Holocene. The ground flora may also have been different from other areas of *Pinus* woodland, for example Speyside, with a higher proportion of grassland than heath vegetation.

The *Pinus* woodland that existed at Geldie Lodge, with *Betula* of greater importance and a more abundant heath field layer, probably bears a greater similarity to woods in other areas of Scotland. Canopy variability at Geldie Lodge was slightly greater than at the lower altitude sites, with variation throughout the mid-Holocene. Fire is implicated in the development of the Geldie Lodge woodland assemblage at one point at least. Evidence of fire and its effects is found in the pollen assemblage from *c.* 6660 to 6450 cal BP and is supported by evidence from Clark's (2003) Coleopteran assemblages.

The short sequence from White Bridge shows only the fragmentation of woodland, and seems to represent a transition in woodland structure between Doire Bhraghad and Geldie Lodge. Fragmentation of woodland occurred with similar timing to that at Doire Bhraghad, but the woodland may also have included *Betula* in addition to *Pinus*. The higher proportions of heath taxa in the assemblage probably relates to the late Holocene date of the assemblage.

7.10 The origin and significance of minerogenic sediment within peat at Doire Bhraghad

Increases in the relative proportion of mineral matter in the Doire Bhraghad sediment sequence are important features. Percentage LOI of peat at Doire Bhraghad falls from 80% to 65% between *c.* 8200 and 5950 cal BP, and to 25% by *c.* 5300 cal BP. Recovery is more rapid; LOI exceeds 80% by *c.* 3700 cal BP. Increases and decreases in mineral sediment accumulation are gradual, not abrupt (Section 4.5). One vegetation change centred on the period *c.* 5850-4800 cal BP is a decline in Cyperaceae pollen percentages and an increase in numbers of spores of *Sphagnum* (Figure A.1a and b). Cyperaceae percentages and concentrations fall from *c.* 9200 cal BP, and then recover between *c.* 6800 and 5900 cal BP (130-115cm) (A.1a and b), coincident with an increase in organic content and recovery in LOI values. *Sphagnum* values begin to increase from *c.* 6000 cal BP but are not important until *c.* 3000 cal BP. Together these indicate changes in the types of organic matter forming in the basin at Doire Bhraghad, but it is difficult to explain the change in sediment accumulation in relation to the change in mire type.

Drying of the regional climate from *c.* 9200 to 5300 cal BP, followed by reversion to a wetter climate, could be implicated in these changes. Gradual drying would have created an increasingly aerobic peat surface, causing peat mineralization and culminating in cessation of organic accumulation, the hiatus then broken by a return to wetter conditions. To address this there are several internal tests at Doire Bhraghad that can be applied:

- increases in the proportions of corroded pollen, especially in susceptible taxa such as *Betula* and Poaceae, should be seen but they are not apparent (Figures A.1a and A.1b);
- sediment accumulation should decline dramatically, but the dating model for Doire Bhraghad suggests only a modest decline (Figure 4.5);
- a hiatus in deposition would be the end-point, but this cannot be established from the radiocarbon dates available or with reference to abrupt changes in pollen proportions and concentrations;
- total land pollen concentration values might be a similar but more sensitive measure as they should increase but Figures A.1f-k do not show this;
- *Pinus*, as would be expected in a drying climate (Binney 1997, Davies 2003a), dominates the vegetation assemblage;
- fire would become increasingly important (Tipping 1996), but charcoal counts do not increase until *c.* 4800 cal BP, after the postulated 'driest' period.

Regional climatic change to drier conditions causing peat mineralization is not supported unequivocally by the internal evidence at Doire Bhraghad. The analysis of changing peat humification from Geldie Lodge (Figure 6.2) includes most of this period and because the site is on a water-shedding slope the changes in mire surface wetness it shows are likely to be climatically driven. There is no evidence in this record for gradual directional change in climate, or in the microscopic charcoal record that fire was a consistent and important feature (Figures A.3a).

It is difficult to correlate the detail of the Doire Bhraghad sediment stratigraphy with other regional palaeoclimatic reconstructions. Most recent models of Holocene climate envisage relatively short periods of climatic stability interspersed by rapid change. Dubois and Ferguson's (1985) 'pluvial' episodes (Section 7.2) in the Holocene are dated to *c.* 8200, 7200-6600, 4800-4400 and 3550 cal BP. Short, rapid shifts in climate are at odds with a gradual directional shift in climatic conditions extending over thousands of years (Mayewski *et al.* 2004). This supports the view that peat accumulation at Doire Bhraghad was not responding to shifts in regional climate. One of Langdon *et al.*'s (2003) phases of increased mire surface wetness in south east Scotland between *c.* 5850 cal BP, and *c.* 5000 cal BP correlates well with part of the sediment record at Doire Bhraghad but not in the gradual nature of the changes seen at this site.

Gradually increasing precipitation driving runoff and soil erosion could result in in-washing of minerogenic soil from the surrounding valley floor and the steep basin slopes, eventually swamping organic accumulation. Human activity, rather than or in addition to climate changes, may have disturbed plant communities and soils. This can also be subjected to internal tests:

- increased sediment supply should result in decreasing pollen concentration values: this is not apparent, concentrations increase slightly, especially from *c.* 5850 to 4800 cal BP though pollen concentration values decline after *c.* 4800 cal BP, mainly due to reduced *Pinus* pollen concentrations;
- increased sediment accumulation rates should be seen, but Figure 4.5 indicates that sediment accumulation rates decreased until *c.* 2000 cal BP

(Figure 4.5, Table 4.5), though this may be due to the limited number of radiocarbon dates;

- the incidence of fire in the landscape should decline. Charcoal percentages greatly increase only after *c.* 4800 cal BP, though these changes are much more abrupt than increases in percentage LOI;
- increased erosion of the basin slopes should result in vegetation disturbance, but there are no increases in taxa, such as *Pteridium aquilinum* or *P. lanceolata,* that would indicate this.

There is little clear internal evidence for soil erosion providing a source of mineral sediment and in the region, although fluctuations in pollen assemblages are found, they are not of the same character as at Doire Bhraghad. Of Binney's (1997) Gleann Einich sites, Allt A'Phris-Ghiubhais (500m OD) shows vegetation disturbance and a shift from dense to open woodland between *c.* 6300 and 5700 cal BP. Higher, more sensitive sites, Carn a'Phris Ghiubhais (610m) and Lochan Odhar (730m), show rapid, rather than gradual changes. Between *c.* 7800 cal BP and 3500 cal BP shifts between more open or less open *Pinus* canopy, are typically in the order of 300-400 cal years. The much lower altitude sequences from Loch Davan and Braeroddach Loch (240m OD, Edwards 1978) show largely unchanging pollen assemblages and sediment records between *c*. 3500 and 7400 cal BP.

The lack of clear correlation between available regional palaeoclimatic data and the Doire Bhraghad evidence suggests that local factors overrode regional drivers. At first sight the minerogenic bands seemed clearly inwashed, and in the field were referred to as such. However, whether regional or local, the nature of such drivers is unclear. As the currently available evidence is insufficient to clearly indicate the processes leading to the stratigraphy seen, it is appropriate to speculate on additional evidence which, if available, could resolve the difficulties.

While internal evidence does not support a hiatus in deposition, new radiocarbon dates, refining the dating model, could confirm or refute this with more confidence. The single date from above the minerogenic band is the only date from within the period of decreased LOI percentage and is insufficient to establish the existence of a hiatus in accumulation (Ashmore *et al.* 2000). New dates from above and below the minerogenic band should better indicate the rate of accumulation, currently interpolated, from the base of the sequence to above the minerogenic band.

A more detailed examination of algal and fungal palynomorphs with reference to van Geel (1978) might reveal fresh evidence regarding the status of open water during the entire period. This may confirm or rule out the drying of the peat surface. Re-analysis of the minerogenic band, without HF treatment would allow the presence or absence of diatoms to be established, potentially indicating the status of open water throughout the sequence.

The period from *c.* 5800 to 4800 cal BP coincides with drying of mire surfaces in northern Scotland (Gear and Huntley 1991, Charman 1994, Moir *et al.* 2010). Drying of mire surfaces is linked with the northward expansion of the Azores High and colonisation by *Pinus*. The widespread evidence for this event suggests that drying of the mire surface also occurred at Doire Bhraghad, despite the limited evidence for it, the gradual change being a result of local factors stemming from the relatively continental climatic conditions in the area. Finer resolution analysis of the core might reveal evidence for a very short event missed in the current investigation. A fresh examination of, for example, macro-charcoal particles, may also provide fresh evidence of a causal mechanism. The transition to minerogenic sediment may be due to an entirely different process, for example animal use as a mud wallow may have prevented tree colonisation. Clark's Coleopteran analysis at Geldie Lodge included a period (*c.* 7000-5700 cal BP) where species associated with dung were identified, therefore an analysis of Coleoptera at Doire Bhraghad may reveal similar evidence. Changes in the pollen assemblage during this period are also considered in Section 7.11.

Summary

It seems likely that the decline and recovery in LOI between *c.* 8200 and 3700 cal BP is related to important changes in the conditions at Doire Bhraghad. The two main scenarios of change, gradual drying of the mire surface followed by reversion to wetter conditions or increasingly wet conditions followed by drying, are not supported by the internal evidence. Evidence of regional change, including the Colorimetric transmission curve from Geldie Lodge, is not supportive of gradual change to climate over such a long time period, suggesting that regional change in Doire Bhraghad is at least masked by local factors, but the drivers remain unclear.

Drier conditions between *c.* 5800 to 5000 cal BP, followed by increasingly wet conditions are prevalent elsewhere in Scotland and would be expected to affect Doire Bhraghad but further testing of this is not possible without additional data. Refinements to the dating model, particularly around the minerogenic band are likely to provide the simplest means of determining causal change. Clarification may also be provided by more detailed examination of non-pollen palynomorphs and diatoms. Finer resolution palynological analysis may reveal factors not located in the present analysis, for example, evidence of fire affecting the basin. Local evidence of fire might also be revealed by macroscopic analysis of the sediments before and during the minerogenic band. An entirely new analysis of Coleoptera from the Doire Bhraghad sediment may provide evidence of the causes of change in the basin.

7.11 Canopy variation, fragmentation and disappearance of *Pinus*

The canopy at Doire Bhraghad did not clearly reflect the climate change at *c.* 8200 cal BP widely identified in the Northern Hemisphere (Mayewski *et al.* 2004, Nesje *et al.* 2006), but remained relatively stable until *c.* 4800 cal BP. The first indication of change to the canopy at Doire Bhraghad occurs when influx and concentration fall abruptly at *c.* 4800 cal BP (Figures A.1a and b). A low ‘plateau’ in influx from *c.* 4800 to 1600 cal BP coincides with variable, gradually declining percentages and much higher charcoal percentages. *Pinus* pollen percentages above 40% TLP and continued presence of stomata show that *Pinus* remained important around the basin until *c.* 2200 cal BP. Unchanging percentages of *Empetrum* suggest no further fragmentation until this time, but changes to the AP/NAP ratio, initially due to increases in Poaceae and, from *c.* 3000 cal BP, increases in *Calluna,* are in agreement with canopy fragmentation. But only the assemblage at Doire Bhraghad shows unambiguous change, around the transition to a wetter climate between *c.* 3900 and 3500 cal BP demonstrated by Anderson *et al.* (1998). As suggested above (Section 7.7) it is possible that the late changes at Doire Bhraghad were due to the near absence of other arboreal taxa in competition with *Pinus. Pinus* remained in the local area until *c.* 1800 cal BP, probably as scattered individuals in *Calluna* heath. *Pinus* became increasingly important again from *c.* 1000 cal BP.

Vegetation at Geldie Lodge showed much greater fluctuations than Doire Bhraghad, with interchange between dominance by *Pinus,* Ericaceae and Poaceae. Charcoal totals at Geldie Lodge are also higher more consistently than at Doire Bhraghad. Neither site has large proportions of the herb taxa associated with human disturbance, but Geldie Lodge does show rises of Poaceae and heath taxa, good indicators of woodland change, from as early as *c.* 7200 cal BP. Like Doire Bhraghad, the Geldie Lodge assemblage has periods of low *Pinus* pollen influx as *Pinus* percentage declines. The link between low influx, declines in percentage and woodland fragmentation is exemplified by the final fragmentation phase prior to disappearance, between *c.* 4800 and 2800 cal BP. As at Doire Bhraghad, reference to the *Empetrum* percentage does not indicate an opening canopy during this period, but change to the AP/NAP ratio does, initially due to increases in Poaceae and, from *c.* 3800 cal BP, from *Calluna*. The stomatal record also shows disappearance of local trees during phases of low percentage and influx (e.g. *c.* 6050 to 5650 cal BP) and is sporadic during the final phase of *Pinus* disappearance. The disappearance of *Pinus* from Geldie Lodge at *c.* 2800 cal BP preceded the disappearance of *Betula*. Woodland is replaced by open heath, rather than grassland.

Canopy fragmentation was greater at White Bridge than at Doire Bhraghad. The disappearance of *Pinus* from the White Bridge site occurred at about the same time as Doire Bhraghad populations changed to scattered individuals of *Pinus* set within *Calluna* heath. This more extensive fragmentation is probably related to the initial greater openness around the core site at White Bridge, but may also be as a result of more intensive human activity in Glen Dee (Section 7.12). As at Doire Bhraghad from *c.* 1000 cal BP, increases of *Pinus* percentage and influx at White Bridge from *c.* 700 cal BP suggest recovery of *Pinus*. Percentages suggest a local re-appearance but there are no stomata recorded, and very low influx suggests that this could be input of extra-local *Pinus* pollen. This resurgence is not visible in the Geldie Lodge assemblage, and may also relate to human activity.

Final disappearance of *Pinus* from Geldie Lodge at *c.* 2800 cal BP, from White Bridge at *c.* 2000 cal BP, and fragmentation of woodland at Doire Bhraghad suggests that pine woodland contracted eastwards as change affected the whole area.

In contrast to Doire Bhraghad, fragmentation at Loch Maree is recognised as early as *c.* 7400 cal BP and became more rapid from *c.* 4900 cal BP (Birks 1972). At Loch Pityoulish, *Pinus* woodland was unchanged until *c.* 5700 cal BP, when *Betula* and *Quercus* replaced *Pinus*, but canopy fragmentation began at *c.* 3500 cal BP. The assemblage in the Loch an Amair catchment remained dominated by trees until the late-Holocene with reduced tree cover from *c.* 2200 cal BP (Froyd and Bennett 2006). In western Glen Affric *Pinus* began to decline at *c.* 4000 cal BP and by *c.* 2000 cal BP pine had disappeared from the landscape (Davies 2003a and b; Shaw 2006). This suggests that woodland was more stable in Glen Lui than in most other areas, especially western Scotland.

There is some correlation between canopy fluctuations at Geldie Lodge and elsewhere. The distinct canopy fragmentation at Geldie Lodge from *c.* 6650 to 6400 cal BP may correlate with the beginning of a canopy reduction at Allt A'Phris Ghiubhais (*c.* 6300 to 5600 cal BP, Binney 1997). At Geldie Lodge, falls in *Pinus* percentage from *c.* 6100 to 5200 cal BP and disappearance of stomata between *c.* 6100 and 5550 cal BP overlap with declines in *Pinus* percentage and sporadic presence of stomata at Torran Beithe in Glen Affric between *c.* 5600 and 5000 cal BP (Davies 2003a). Closure of the canopy at Geldie Lodge between *c.* 5200 and 4400 overlaps with a rise in treeline and canopy closure in Gleann Einich (*c.* 5700-4600 cal BP). A slightly denser canopy from *c.* 4300-3900 cal BP correlates with Anderson's (1998) shift to a drier climate at *c.* 4300 cal BP. Binney (1997) regards canopy closure as correlating with colonisation of Northern Scotland by *Pinus* (*c.* 5000-4500 cal BP, Gear and Huntley 1991; *c.* 5200-4500 cal BP, Charman 1994). These changes to canopy density and treeline positions in the Cairngorms are in agreement with the northward expansion of the Azores high. Denser colonisation of the mire at Geldie Lodge is best explained by drying of the mire surface.

There is also good evidence for canopy closure at Doire Bhraghad at this time, but there are no trees in the basin or on the mire. Percentage, concentration and influx values all increase during this phase, in agreement with a dense canopy, but stomata are absent, for *c.* 900 cal years, indicating an absence of very local *Pinus* individuals. This covers the period in which LOI was very low and includes the minerogenic band considered at length in Section 7.10. The timing of this transition suggests drying of the mire surface at Doire Bhraghad as well, but critically increases of corroded pollen do not occur (Section 4.5 lpaz DB3a and Section 7.10).

A canopy opening in itself is a natural effect of woodland cycling. A similar combination of high pollen percentage and no stomata is recorded in Shaw's (2006) ANI core from Glen Affric (Shaw 2006). A clearing is also recorded at Geldie Lodge at *c.* 6000 to 5400 cal BP. The length, timing and sedimentary context makes the clearing at Doire Bhraghad unusual. Drying of mire surfaces at this time seems to have led to colonisation by *Pinus* in many other places in Scotland (Gear and Huntley 1991, Charman 1994, Moir *et al.* 2010), but not at Doire Bhraghad. As concluded in Section 7.10, the causal mechanisms driving the stratigraphic changes are unclear.

The clearest regional correlation from Geldie Lodge relates to the beginning of the disappearance of *Pinus* from *c.* 3900 cal BP. This is later than the end of the southward movement of *Pinus* reported by Gear and Huntley (1991), and toward the end of the period of permanent reductions in *Pinus* pollen in northern Scotland compiled by Anderson *et al.* (1998). This period, between *c.* 4800 and 3800 cal BP included the fragmentation of *Pinus* woodland at Binney's (1997) lowest site in Gleann Einich, from *c.* 4500 cal BP but slightly precedes the downward retreat of treelines on Rannoch Moor (*c.* 3500 cal BP, Ward *et al.* 1987). The more southerly locations of these sites allows them to remain in agreement with even a fairly rapid southerly shift of the Azores High. The slightly different timing of the onset of fragmentation at Geldie Lodge could be attributable to the less exact dating model or to site-specific slightly drier, more ‘continental’ climate nature of Glen Geldie (Figure 3.3). Fragmentation becomes clear at Doire Bhraghad from around this time; the less dramatic and slower change there could also be attributable to the increasingly continental conditions eastwards down Glen Dee.

The disappearance of *Pinus* from Geldie Lodge was coincident with the change to *Calluna* heath at Binney’s (1997) three lower sites in Glean Einich at *c.* 2800 cal BP. Binney regarded the disappearance of *Pinus* from Gleann Einich as driven by regional declines in temperature and seasonality. These climatic changes have been linked with decreasing human activity, primarily in northern Scotland (Anderson *et al.* 1998). The assemblage at Binney’s highest site, Moine Mhor (930m), may show local *Pinus* at *c.* 3200 cal BP, which Binney suggests may reflect its survival remote from human activity.

Fragmentation and disappearance of woodland from *c.* 4000 cal BP onwards is in agreement with similar changes in Speyside, Gleann Einich, Glen Affric and North West Scotland. At all Mar Lodge sites *Pinus* was replaced by *Calluna* rather than by other arboreal taxa. Retreat of *Pinus* from Geldie Lodge and fragmentation of the woodland at Doire Bhraghad also correlates with lowering of the treeline in Finland after *c.* 4000 cal BP (Kultti *et al.* 2006), in the Swedish Scandes in the mid-late Holocene (Kullman and Kjallgren 2000) and retreat from the maximum northern extent of *Pinus* in the Kola Peninsula (Boettger *et al.* 2003, Kremenetski *et al.* 2004). All these oscillations are associated with declining temperature and seasonality in the later Holocene. Changes in Mar Lodge are probably related to decreased continentality, with the greatest impact in the most exposed, least continental site at Geldie Lodge. Doire Bhraghad had the most sheltered conditions throughout the Holocene; this may have ameliorated the effects of climate change.

Summary

Woodland around Doire Bhraghad remained unchanged until *c.* 4800 cal BP, after canopy disintegration had begun in most other areas of Scotland but the longevity of *Pinus* woodland in Mar Lodge, particularly at lower altitudes, shows firm affinity with other core areas of woodland. *Pinus* was more dominant in the woodland of Glen Lui than most other areas in Scotland whilst woodland history at Geldie Lodge bears greater similarity to other core areas. The complete disappearance of woodland from Glen Geldie shows it to be somewhat peripheral.

The persistence of dense canopy *Pinus* in Glen Lui may have been due to the absence of arboreal competition. *Pinus* was present in the Doire Bhraghad basin until *c.* 2200 cal BP and probably remained in the local area throughout the Holocene; as woodland fragmented it was replaced by *Calluna* heath rather than *Betula* woodland. In contrast the canopy at Geldie Lodge fluctuated throughout the Holocene, before a final fragmentation and disappearance between *c.* 4800 and 2800 cal BP, when *Pinus-Betula* woodland was replaced by *Calluna* heath. The sequence at White Bridge shows more variable influx values for *Pinus* pollen, even during periods of relatively high percentages. This suggests that at Mar Lodge, variable influx is a good indicator of canopy fragmentation.

Other measures of woodland openness are typically in agreement with *Pinus* pollen percentage and influx. Stomata are usually present only when *Pinus* pollen percentages and influx are relatively high; falls in *Pinus* percentage and variable or low influx are usually accompanied by increases in non-arboreal pollen. An important exception to this is at Doire Bhraghad between *c.* 5800 and 4800 cal BP, where very high *Pinus* pollen percentage and influx are combined with low non-arboreal pollen totals but also with the absence of stomata. This period describes a clearing in the woodland, which may be related to the changes in sediment accumulation which cannot be fully explained.

Final disappearance of *Pinus* from Geldie Lodge and White Bridge was just prior to its disappearance from the Doire Bhraghad basin. The timing of this suggests that *Pinus* woodland disappeared or fragmented as deteriorations in regional climate took place. The slightly different response of woodland at White Bridge compared to Doire Bhraghad may be indicative of greater human activity.

7.12 Human impact

The presence of people in the Mar Lodge area is not generally supported by archaeological finds of settlement until the 17th Century AD (Section 3.3), but the finds of Mesolithic flints at Geldie Lodge and at White Bridge (Ballin 2003, Clarke 2007, Section 2.3) show that people were present well before that. The sequences at Doire Bhraghad and Geldie Lodge date to the Mesolithic period, prior to *c.* 6000 cal BP, but possible evidence of local human activity from that time is found only at Geldie Lodge.

The earliest evidence for human activity at Geldie Lodge spans most of lpaz GL1, (*c.* 7550 to 7100 cal BP) and comes in the form of very high charcoal values associated with a fluctuation in tree canopy density. Charcoal values at Geldie Lodge declined after *c.* 7100 cal BP, but are typically higher than values at Doire Bhraghad until *c.* 4800 cal BP, when charcoal in the Doire Bhraghad assemblage abruptly increases. High charcoal percentages in palynological assemblages are sometimes assumed to indicate human presence, but this is an assumption and must be considered carefully (Edwards 1988, Tipping 1996). Edwards (1988) mentions some studies in Scotland that link Mesolithic aged microscopic charcoal with human activity, but prefers to link activity with changes to pollen assemblages. In the Western Isles high charcoal values and changes to pollen assemblages have been associated with archaeological evidence of Mesolithic occupation (Bohncke 1988, Edwards 1988, Gregory *et al.* 2005).

A major fluctuation in canopy density at Geldie Lodge, between *c.* 7000 and 6000 cal BP, is associated with a large peak in Poaceae and sporadic appearances of pollen taxa, shown by Mazier *et al.* (2006) to indicate grazing pressure (Section 6.5, lpaz GL2). The regular presence of large cereal-type grains (*Hordeum* type) in lpaz GL2 is probably indicative in this context only of the high incidence of certain wild Poaceae genera, not of crop cultivation (Anderson 1979). It is unclear to what extent sporadic appearance of some of the suite of pollen taxa associated by Mazier *et al.* (2006) with grazing pressure can be regarded as indicative of anthropogenic activity. This uncertainty suggests that a sound approach is to assume that these pollen taxa do not, of themselves, indicate local human activity. Charcoal is almost absent from *c.* 7100 to 6700 cal BP, but becomes more important after this and is then likely to have affected the local vegetation (Section 6.5 lpaz GL2).

From *c.* 6000 to 4200 cal BP, the evidence for human occupation at Geldie Lodge decreases. At Doire Bhraghad there is an abrupt increase in charcoal and Poaceae percentages from *c.* 4800 cal BP. There is a less dramatic increase in charcoal values at Geldie Lodge from *c.* 4200 cal BP, and White Bridge has moderately high charcoal values from peat inception at *c.* 3600 cal BP. As discussed in Section 7.9, these charcoal increases are associated with canopy fragmentation at all sites. Of greater significance may be the start of sporadic appearances of *Plantago lanceolata* at Geldie Lodge and Doire Bhraghad from *c.* 4200 cal BP, and consistent presence from *c.* 3350 cal BP at White Bridge.

At Doire Bhraghad, *Plantago lanceolata* is most consistently present between *c.* 4200 and 1200 cal BP, and at Geldie Lodge between *c.* 3000 and 1200 cal BP, but it always shows low percentages and is generally rather sporadic. At Doire Bhraghad appearance of

P. lanceolata, together with evidence of fire and other canopy disturbance, may be enough to indicate human activity. High productivity of *P. lanceolata* pollen and its easy dispersal (Brostrom *et al.* 2004) suggests that it is indicative only of extra local or regional activity (Favre *et al.* 2008, Mazier *et al.* 2006, Tinner *et al.* 2007). In lpaz GL5 and GL6 (from *c.* 2800 to 1200 cal BP) increased *P. lanceolata* percentages occur with sporadic presence of *Hordeum* type pollen. There is an increased likelihood of this cereal pollen being from cultivated crops, but the low percentages and sporadic presence still suggest an extra-local input.

At White Bridge, *P. lanceolata* is consistently present and has slightly higher percentages, perhaps high enough to suggest local activity. From *c.* 3079 to 2760 cal BP, there are some members of the suite of taxa associated with grazing by Mazier *et al.* (2006) (Section 5.5 lpaz WB2a). Their slightly more consistent presence, in association with *P. lanceolata,* and higher charcoal values suggest a stronger likelihood of local human activity. Local human activity becomes less clear after *c.* 2500 cal BP, as *P. lanceolata* and Poaceae percentages decline, charcoal values diminish and those of *Pinus* become more important.

After *c.* 1200 cal BP, evidence of human activity declines still further at all sites. This is less noticeable at Geldie Lodge, but at Doire Bhraghad and White Bridge there are declines in percentages of *P. lanceolata*, Poaceae and charcoal. Towards the surface of both lower altitude sequences there are also small increases in *Pinus* percentage and influx, indicative of a woodland recovery.

There was a Mesolithic human presence on Deeside, as shown by microlith finds in Mar Lodge and elsewhere, but in lower Deeside major changes to vegetation assemblages are not recorded (Edwards 1978, Huntley 1994), and the few assemblages identified as indicative of human impact are disputed (Tipping 2007). Pollen evidence for local human activity at any of the Mar Lodge sites is not very strong, with much of the evidence derived from association with increases in charcoal, or showing change that could be natural.

Fire is important in pinewoods (Peterken 2001). Historical evidence shows a likely fire return period of 80-100 years (Bruce and Servant 2003) in Glen Tanar, East Aberdeenshire. This makes it very unlikely that woodland in Glen Lui remained untouched by fire for *c.* 4500 cal years. If charcoal percentages in the Doire Bhraghad assemblage before *c.* 4800 cal BP are taken as a baseline showing natural incidence of fire, it could be concluded that charcoal at Geldie Lodge is indicative of anthropogenic activity. Edwards (1978) also found low charcoal values in sediments of the same age in the Howe of Cromar, but site differences, such as the higher altitude and less dense canopy at Geldie Lodge, makes direct comparison unwise.

Also significant is the lack of high charcoal values from Binney's (1997) sites in Gleann Einich. Binney makes no mention of charcoal as a significant factor in the development of the *Pinus* treeline, and regards fluctuations in the canopy and treeline as related to regional climate and local topography and drainage. Fluctuations in arboreal pollen in Gleann Einich (Binney 1997) are similar to Geldie Lodge, showing that woodland change could have occurred without human interference. Geldie Lodge has much higher charcoal percentages than Gleann Einich, which may suggest anthropogenic activity, but which do not provide proof of human presence.

Hornberg *et al.* (2004) are confident that Mesolithic people in Northern Sweden were responsible for changes to the woodland assemblage without the use of palynologically visible fire. Changes to woodland between *c.* 8400 and 8000 cal BP are shown by shifts in the forest floor vegetation, particularly to Poaceae, and by highly variable *Pinus* influx. In the same area Bergman *et al.* (2003) correlate archaeological evidence of Mesolithic settlement with increases in charcoal, possibly from hearths, which Hornberg *et al.* (2004) concede could be natural in more open fire-prone *Pinus* woodland.

The pollen assemblage at Geldie Lodge displays similar characteristics to those of Hornberg *et al.* (2004), including variations in *Pinus* influx and increases in Poaceae. These are accompanied by increases in charcoal, but open woodland would be fire-prone and would attract herbivores that could maintain openings in the canopy. In addition to finding woodland, including *Pinus* indicators, between *c.* 7000 and 5740 cal BP, Clark (2003) identified Coleoptera species associated with dung in a series of consecutive levels. This includes the period of very high Poaceae percentages, indicative of a clearing in the canopy maintained by, presumably, wild animals.

There is no conclusive evidence showing woodland was deliberately fired by humans to optimise hunting *sensu* Simmons (1996), but this is a plausible scenario. A mid-Holocene decline in charcoal (from *c.* 7100 cal BP) in the Geldie Lodge assemblage is earlier than the (mid-Holocene) Mesolithic-Neolithic boundary charcoal decline of Edwards and Whittington (2000). There are indications of increased bog surface wetness at this point (increases in *Sphagnum* and slightly increased colorimetric light transmission) supportive of decreased natural fire. But a decline in charcoal at Geldie Lodge could also represent a change in land use. For example, people may have visited frequently until *c.* 7100 cal BP but only occasionally after this.

The slightly higher abundance of *Corylus* (Section 7.1 and 7.7) at Geldie Lodge provides a possible explanation for human presence at Geldie Lodge but not at Doire Bhraghad. Hazel nuts formed an important part of the Mesolithic diet and the initially greater abundance of *Corylus* at Geldie Lodge would perhaps have encouraged people to frequent the area. A decrease in the abundance of *Corylus* after *c.* 7100 cal BP would have removed this stimulus, but the level of certainty in the pollen record make this conclusion somewhat tentative. However, if this interpretation is pursued, high charcoal values prior to *c.* 7100 cal BP may be partly derived from hearths, but after this principally from burning vegetation. Grazing indicators at Geldie Lodge between *c.* 7100 and 6000 cal BP are from wild animals, encouraged to the area by burning. The length of time for which this clearing is maintained, may favour a human role in its maintenance. Human hunting activity would help to concentrate both herbivores and their associated Coleoptera.

After *c.* 6000 cal BP, activity in the area was much diminished. For nearly 2000 cal years Glen Geldie had no palynologically visible human impact. The same is true of Doire Bhraghad, possibly until *c.* 4800 cal BP. This is in contrast to lower Deeside where increased impact after *c.* 5800 cal BP is illustrated by a cache of carbonised cereal grains, including *Triticum* spp. and *Hordeum vulgare* (Tipping 2007). In neighbouring Donside, evidence of Neolithic people is still rare and despite more extensive archaeological surveys, settlement is unknown above 150m (Gannon *et al.* 2007). On lower Deeside little is known about where the cached cereals were grown. Conditions in lower Deeside even on cleared ground are considered marginal for growth of crops (Edwards and Ralston 1984). It is therefore unlikely that early farmers had a strong presence where conditions were even less ideal.

The clearing that developed at Doire Bhraghad between *c.* 5800 to 4800 cal BP may have had a human origin but there is no evidence to support this (Section 7.9). Even after *c.* 4800 cal BP, the main indicator of activity is from large increases in charcoal percentages. As at Geldie Lodge the collapse in *Pinus* pollen influx and increases in Poaceae could be a natural process but could also be caused by human activity; the possibility of a causal link with human activity is reinforced by the appearance of *P. lanceolata* from *c.* 4200 cal BP. Nonetheless, the low percentages of *P. lanceolata* suggest that people were active within the area, but helping to fragment the woodland, rather than causing fragmentation. It is possible that anthropogenic indicators become apparent as a result of natural canopy thinning. In Glen Affric agricultural expansion even in the Bronze Age was still strongly linked to local ecosystem processes (Davies 2007).

From *c.* 4000 cal BP, when indicators of presence increase again at Geldie Lodge, it is probable that people were living, farming and keeping animals at least within the extra-local area, and that their activities probably detrimentally affected the woodland. An interval from *c.* 3400 to 2800 cal BP, in which charcoal diminishes, *P. lanceolata* disappears, Poaceae declines and *Pinus* recovers slightly, suggests decreased impact. All these indicators are reversed after *c.* 2800 cal BP, suggesting human impact to be implicated in the final disappearance of *Pinus* from Glen Geldie.

Whether similar activity took place around Doire Bhraghad is less clear. The still relatively dense woodland and more enclosed valley floors may have restricted activity. Though the canopy was fragmenting, it remained denser than at Geldie Lodge and may still have restricted input of extra-local pollen indicators of human activity. This is less true of the White Bridge assemblages, where local activity is very likely, especially between *c.* 3100 and 2500 cal BP. It is likely that in upland areas such as Mar Lodge, grazing was the more widespread agricultural activity, with cultivation limited to alluvial soils (Davies 2007). Such soils are more common within the local area of White Bridge than other sites in Mar Lodge. Nonetheless pollen evidence at Doire Bhraghad and White Bridge is restricted to indicators of grazing rather than of cultivation, with percentages indicative of low intensity activity. It is possible that the more open canopy, and more open, shallow sided valley at Geldie Lodge was more attractive to early farmers than the areas around Doire Bhraghad and White Bridge, despite the higher altitude (Davies 2007).

The increase in evidence of human impact after *c.* 4000 cal BP is in agreement with a general increase of human activity in north east Scotland in the late Neolithic and early

Bronze Age, and in upland areas throughout Scotland. Increasingly clear activity after *c.* 3500 cal BP is seen from east and west sides of the Cairngorms and increased impact on vegetation is apparent in Speyside (O'Sullivan 1976) and the Howe of Cromar (Edwards 1978). This increase is not found by Huntley (1994) in the Morrone Birkwoods, suggesting that the relatively poor soil conditions and isolation of Upper Deeside continued to deter settlement. This may have somewhat in common with Loch a'Chnuic in Speyside (O'Sullivan 1976) where grazing led to gradual deforestation over 2500 to 3000 cal years.

The development of the Mar Estate as a semi-autonomous fiefdom (Section 3.1.5) may be reflected in the disappearance of *P. lanceolata* and decrease of Poaceae from *c.* 1200 cal BP at both Doire Bhraghad and White Bridge. It is possible that this reflects a decrease in population in Mar Lodge as the Earls of Mar reserve the area for hunting. Increases in *Pinus* after this may demonstrate increases in woodland as people are removed but equally may reflect improved conditions for *Pinus* during the medieval warm period. The pollen assemblages presented here lack sufficient detail to the show rapid deforestation in the 18th and 19th centuries when the woodlands were cleared by loggers (Section 3.1.5).

Summary

Flint finds indicate that Mesolithic people were certainly active in the valleys of Mar Lodge. Palynological evidence is not overwhelming, but at Geldie Lodge, is supportive of presence between *c.* 7500 and 6000 cal BP. Human activity is suggested by high charcoal percentages, which are unusual in the early to mid Holocene woodlands in this area. From *c.* 7100 cal BP, and particularly between *c.* 6700 and 6450 cal BP, human hunting activity is implicated in the changing vegetation assemblage, with evidence including high Poaceae and decreased arboreal pollen percentages, charcoal and Coleoptera. Commonly used indicators of vegetation disturbance such as *P. lanceolata* are still rare. Evidence of human activity at Geldie Lodge disappears between *c.* 6000 and 4000 cal BP.

There are no indications of humans at Doire Bhraghad until *c.* 4800 cal BP; as at Geldie Lodge, high charcoal values are an initial indicator of human presence, at Doire Bhraghad these are combined with high Poaceae values suggesting interference in the vegetation assemblage. The appearance of *P. lanceolata* from *c.* 4200 cal BP strengthens the case for human presence, but low percentages suggest activity within a woodland canopy that was already fragmenting.

Increasingly apparent human presence after *c.* 4000 cal BP is in agreement with evidence from lower Deeside and Donside (Gannon *et al.* 2007, Tipping *et al.* 2007). However, evidence from Donside and lower Deeside suggests a large settled population to be unlikely, making the series of indicators of cultivation at Geldie Lodge fairly surprising but very important. The probably marginal conditions in Mar Lodge, and pollen assemblages from all three sites, are in agreement with pastoralism forming a major part of early subsistence by people in the area. Grazing of domesticated or semi-domesticated animals and some cultivation probably led to increases in the natural fragmentation of woodland. The clearest evidence for this is from Geldie Lodge.

8 Conclusions

8.1 Introduction

Chapter two addressed the extent and behaviour of Scottish pinewoods by reviewing the current knowledge of appearance and location of *Pinus sylvestris* in Scotland. This review was organised under ten headings (Section 2.4), to develop comparisons between the Mar Pinewoods and areas considered likely to have a similar vegetation history. Explanation of the histories of both Scottish woodlands and those of Mar is facilitated by the careful consideration of *Pinus sylvestris'* ecology (Section 2.2). This provided a framework with which to develop an understanding of the important but almost un-studied history of *Pinus* in upper Deeside.

The specific hypotheses and aims of this study (Section 2.8) provide the key points of this section within the context of the headings in Section 2.4, excepting the relationship between local tree presence and sub-fossils, which was satisfactorily addressed in Section 2.6. The conclusions of this study extend knowledge of the way in which *Pinus* woodland developed in Scotland and the Mar Lodge area and how palynological assemblages show this. Conclusions will be relevant to the management of woodlands in Mar and elsewhere in Scotland.

8.2 First appearance of *Pinus*

Stomatal records from Doire Bhraghad show that *Pinus* was present in the area from at least *c*. 9600 cal BP, earlier than any other area of Scotland except Loch an Amair in Glen Affric; this initial colonisation at Doire Bhraghad represents a chance colonisation of a favourable site by *Pinus*. Stomatal counts in the palynological analysis at Doire Bhraghad confirm the presence of *Pinus c*. 1000 cal years earlier than prior analyses in upper Deeside have suggested. The date of colonisation of other locations in Mar Lodge was not established, but at Geldie Lodge (500m OD) *Pinus* was abundant by *c*. 7550 cal BP.

8.3 Establishment and woodland expansion

At Doire Bhraghad a gap of *c*. 400 cal years separates the first stomatal record from the increases in pollen percentage, indicating the increase in *Pinus* abundance. This is similar to the findings of Froyd (2005) in Glen Affric, suggesting that such a delay may be a common aspect of colonisation of an area by *Pinus*, rather than a facet of pollen taphonomy, for example, in a lacustrine environment. At Doire Bhraghad it is likely that there were two generations of *Pinus* between *c*. 9600 and 9200 cal BP, but they probably do not represent a local succession. Instead *Pinus* remained rare in the landscape and a distal source of *Pinus* seed led to two separate colonisations of the Doire Bhraghad basin. As a rare component of the woodland *Pinus* probably failed to produce viable seeds and the persistence of *Betula* maintained conditions to which *Pinus* was poorly suited. As with first colonisation only the record from Doire Bhraghad records the increase in rise in *Pinus* pollen percentages, but this increase precedes increases in pollen abundance everywhere in Scotland except Loch Maree in the north west Highlands.

8.4 Woodland before *Pinus*

Before the first record of *Pinus* the woodland assemblage at Doire Bhraghad consisted of semi-open *Betula* woodland, with some *Corylus* and *Salix*. The woodland in Mar Lodge is unusual in the Scottish context, as *Corylus* and *Salix* appear to have been relatively unimportant. At Doire Bhraghad *Pinus* initially replaced *Corylus* in the woodland assemblage, then more gradually displaced *Betula*. It is possible that a similar transition took place at Geldie Lodge but the pollen assemblage suggests *Betula* remained a more important component of the vegetation until the late Holocene.

8.5 Arboreal diversity and competition

The records from Doire Bhraghad and Geldie Lodge suggest that the arboreal assemblages in Mar Lodge were relatively species poor compared to other areas of *Pinus* woodland in Scotland. In addition to *Pinus,* only *Betula* is likely to have been present at all three sites. *Betula* was relatively important at Geldie Lodge until *c*. 3000 cal BP, but had disappeared from Doire Bhraghad by *c*. 8600 cal BP. *Corylus* disappeared from the local area of Doire Bhraghad by *c*. 9500 cal BP, but may have been present at Geldie Lodge until *c*. 4000 cal BP. *Salix* probably remained present in the local area of both Doire Bhraghad and Geldie Lodge; there is corroborating evidence of *Salix* specific Coleoptera at *c*. 5600 cal BP. *Alnus*, *Quercus* and *Ulmus* were not locally present at any of the three sites in the Holocene.

The stability of woodland at Doire Bhraghad, where *Pinus* is the main or only arboreal taxa, maintaining a closed canopy for *c*. 4500 cal years, suggests that the success of *Pinus* as a woodland species may have been due to the lack of competition from other species. The climatic conditions of upper Deeside, especially related to the altitude, prevented most arboreal taxa from colonising the area. In the absence of arboreal competition *Pinus* remained important on substrates from which it was excluded on lower altitude or less exposed sites. This is reinforced by the sequence from Geldie Lodge where greater variation in the canopy density resulted in changes in the field layer. Competition to *Pinus* may have come from components in the field layer at all three sites, but this is not unambiguously shown. In Mar Lodge variation in local conditions appears to have had a greater effect on the growth of *Pinus* than competition with other tree species.

8.6 Canopy density

This study uses a suite of measures to effectively show the variation in canopy density throughout the Holocene; in addition to *Pinus* percentage, AP/NAP ratios and *Pinus* influx, in particular, provide useful information. There are no instances in which only two of the four measures of canopy density, *Pinus* percentage, *Pinus* influx, AP/NAP ratio and percentage of *Empetrum* are in agreement. However there are several instances when decreasing or variable *Pinus* influx is coincident with an increasing AP/NAP ratio, but *Pinus* percentage remains high or unchanged. This could indicate either that influx gives a better indication of canopy density or be an artefact of the skeletal dating of all the sequences. Palynological richness is less clearly useful as periods of low and high richness do not consistently correlate with periods of closed or open canopy, however fluctuation of richness values do seem to correlate with periods of change in pollen assemblages. This is especially true of the Geldie Lodge sequence. Palynological richness shows no directional change in the Geldie Lodge sequence, in agreement with the constant variation in canopy density indicated by other proxies.

There was a closed *Pinus* canopy at Doire Bhraghad from *c*. 9200 to 4800 cal BP and evidence suggests that the canopy at Doire Bhraghad was always denser than either Geldie Lodge or White Bridge. The *Pinus-Betula* woodland at Geldie Lodge was a closed canopy only at *c*. 7550 cal BP, from *c*. 7000 to 6700, 6400 to 5900 and 5000 to 4800 cal BP and had long periods of semi-open and open canopy. Woodland at White Bridge was probably never a closed canopy, as *Pinus* probably never grew on the mire surface; canopy was densest from *c*. 3320 to 3040 and 2770 to 1930 cal BP. Non-arboreal pollen is significantly more important at White Bridge than Doire Bhraghad but the greater prominence of *Betula* at White Bridge may be related to the proximity of the valley side,

8.7 Vigour, abundance and density and appearance of *Pinus*

The abundance, density and appearance of *Pinus* individuals and woodland was different at Geldie Lodge, White Bridge and Doire Bhraghad. In the absence of arboreal competition, variations in percentage, concentration and influx of *Pinus* pollen at Geldie Lodge are most likely to be related to changes in climate, particularly oscillations in effective moisture. The long period of closed canopy woodland at Doire Bhraghad is strongly indicative of the continual presence of large long-lived trees, perhaps capable of withstanding the changes in climate that affected Geldie Lodge.

Evidence of the physical form of trees growing at the mire sites is provided at Geldie Lodge from a prior study of Coleoptera. *Pityogenes quadridens,* a beetle breeding in thin barked pine, is identified at *c*. 6050 to 5700 cal BP. The context of the palynological assemblage and Coleopteran assemblage suggests that thin barked forms of *Pinus* may be common at Geldie Lodge whenever *Pinus* is present on the mire. Though it does not show that the only trees present in the area were of this type, the typically higher percentage of non-arboreal pollen in the assemblage at Geldie Lodge compared to Doire Bhraghad may be indicative of low incidence of large, long-lived trees at Geldie Lodge. Conversely the stability of the woodland and generally low non-arboreal pollen percentages at Doire Bhraghad may be indicative of large, long-lived trees.

The sequence at White Bridge is too short to be certain that the trees were similar to those at Doire Bhraghad, however the similarity of the sites suggests that this was the case. The sampling resolution of the lower White Bridge sequence (before *c*. 2700 cal BP), *c*. 30 cal years, reveals variations in *Pinus* pollen percentage that may be attributable to the growth, maturity and senescence of very proximal *Pinus* individuals. Separation of possible changes to regional pollen inputs, for example mast years, and local changes to pollen production was not possible from the single core sequence at White Bridge. Such sampling resolution was not approached at either Doire Bhraghad or Geldie Lodge.

8.8 Timing of fragmentation and disappearance of woodland

Fragmentation of woodland is fully recorded at two of the three sites investigated, Doire Bhraghad and Geldie Lodge, and similarities between Doire Bhraghad and White Bridge (basal date *c*. 3600 cal BP) suggest that a substantial period of woodland break-up is also recorded there. There is evidence of woodland fragmentation at Doire Bhraghad from *c*. 4800 cal BP, evidence is ambiguous until *c*. 3900 cal BP but the change is increasingly clear from *c*. 3000 cal BP. The modern trees around Doire Bhraghad suggest that the *Pinus* population has remained viable throughout the Holocene. These areas of Mar Lodge have much in common with the pattern of woodland disintegration in Glen Affric (Section 2.6).

The pattern and timing of woodland break up at Geldie Lodge bears greater resemblance to Loch Sionascaig (Pennington *et al*. 1972). Disappearance of *Pinus* woodland at Geldie Lodge and White Bridge is linked to the shift to a wetter climate after *c*. 3900 cal BP with unambiguous evidence of fragmentation at Doire Bhraghad linked to the same climatic change. Human activity at all three sites may have reinforced natural changes, but evidence from charcoal is ambiguous and pollen indicators indicate only low intensity or regional activity even during the late Holocene. At Doire Bhraghad and White Bridge there is a resurgence in *Pinus* pollen in the last *c*. 1000 cal years which may relate to the prevention of settlement and cultivation by subsistence farmers by the Earls of Mar. A decrease in human activity is supported by a decrease in pollen indicators of grazing (rather than cultivation) identified before *c*. 1000 cal BP, though low sampling resolution makes such a conclusion tentative. The modern absence of *Pinus* from the White Bridge site, may be as a result of the apparently greater historical presence of people in that part of Mar Lodge.

8.9 Vegetation replacing *Pinus*

As would be expected in an area with no or few competing arboreal taxa, *Calluna* replaced *Pinus* as the dominant taxon at all three sites. At Doire Bhraghad scattered *Pinus* remained in the *Calluna* heath. At Geldie Lodge *Betula* may have been found at very low abundances in the local area until *c*. 1000 cal BP, but at White Bridge there is evidence only for *Calluna* heath with *Vaccinium* and *Myrica*.

Despite this, the area around Doire Bhraghad can be regarded an area of core *Pinus* woodland; that is an area of maximum woodland stability from which *Pinus* spreads to colonise or re-colonise other areas as conditions allow. White Bridge may be on the boundary of core woodland in Glen Dee, though disappearance of woodland may be related to human activity. Human activity may also have been implicated for disappearance of woodland from Geldie Lodge, but the less dense canopy and co-dominance of *Betula* suggests the site to be peripheral, an area of less stable woodland to which *Pinus* spreads as conditions allow.

References

Aaby, B. and Berglund, B.E. (1986). Characterisation of peat and lake deposits. Wiley, Chichester. pp. 96.

Allen, J.R.M., Long, A.J., Ottley, C.J., Pearson, D.G. and Huntley, B. (2007). Holocene climate variability in northernmost Europe. Quaternary Science Reviews, **26**, 1432-1453.

Alley, R.B. and Augustsdottir, A.M. (2005). The 8k event: Cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews, **24**, 1123-1149.

Anderson, D.E. (1998). A reconstruction of Holocene climatic changes from peat bogs in north-west Scotland. Boreas, **227**, 208-224.

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

Anderson, S.T. (1970). The relative pollen productivity and pollen representation of north European trees, and correction factors for tree pollen spectra determined by surface pollen analysis from forest. Danmarks Geologiske Unders. Arbog, **96**, 1-99.

Anderson, S.T. (1979). Identification of wild grass and cereal pollen. Danmarks Geologiske Unders.Arbog, **1978**, 69-92.

Ashmore, P., Brayshay, B.A., Edwards, K.J., Gilbertson, D., Grattan, J.P., Kent, M., Pratt, K.E. and Weaver, R.E. (2000). Allochthonous and autochthonous mire deposits, slope instability and palaeoenvironmental investigations in the Borve valley, Barra, outer Hebrides, Scotland. The Holocene, **10**, 7-108.

Austin, P. (2000). The emperor's new garden: Woodland trees and people in Neolithic Britain. *Neolithic Studies Group Seminar Papers 5: Plants in Neolithic Britain and beyond.* (ed. A. Fairbairn), pp. 210. Oxbow, Oxford.

Ballin, T.B. (2004). *Chest of Dee, Crathie and Braemar, Aberdeenshire: The lithic assemblage.*

Bannister, P. (1965). Biological flora of the British Isles: Erica cinerea L. The Journal of Ecology, **53**, 527-542.

Bannister, P. (1966). Biological flora of the British Isles: Erica tetralix L. The Journal of Ecology, **54**, 795-813.

Barber, K.E., Chambers, F.M. and Maddy, D. (2003). Holocene palaeoclimates from peat stratigraphy: Macrofossils proxy records from three oceanic raised bogs in England and Ireland. Quaternary Science Reviews, **22**, 521-539.

Barber, K.E. and Langdon, P.G. (2007). What drives the peat-based palaeoclimate record? A critical test using multi-proxy climate records from northern Britain. Quaternary Science Reviews, **26**, 3318-3327.

Barber, K.E., Maddy, D., Rose, N., Stevenson, A.C., Stoneman, A.C. and Thompson, R. (2000). Replicated proxy-climate signals over the last 2000 yr from two distant UK peat bogs: New evidence for regional palaeoclimate teleconnections. Quaternary Science Reviews, **19**, 481-487.

Bell, J.N.B. and Tallis, J.H. (1973). Biological flora of the British isles: *Empetrum nigrum* L. The Journal of Ecology, **61**, 289-305.

Benn, D.I. and Ballantyne, C.K. (2005). Palaeoclimatic reconstruction from Loch Lomond Re-advance glaciers in the west Drumochter hills, Scotland. Journal of Quaternary Science, **20**, 577-592.

Bennett, K.D. (1984). Post glacial history of *Pinus sylvestris* in the British Isles. Quaternary Science Reviews, **3**, 133-155.

Bennett, K.D. (1988). A provisional map of forest types for the British Isles 5000 years ago. Journal of Quaternary Science, **4**, 141-144.

Bennett, K.D. (1995). Post glacial dynamics of pine (*Pinus sylvestris*) and pinewoods in Scotland. In *Our pinewood heritage, Proceedings of a Conference at Culloden Academy, Inverness, 1994.* (ed. Aldous JR), pp. 23-39. Forestry Commission, Scottish Natural Heritage, Royal Society for the Protection of Birds.

Bennett, K.D. (1996). Late quaternary vegetation dynamics of the cairngorms. Botanical Journal of Scotland, **48**, 51-63.

Bennett, K.D. and Birks, H.J.B. (1990). Postglacial history of alder (*Alnus glutinosa* (L) gaertn.) in the British Isles. Journal of Quaternary Science, **5**, 123-133.

Bennett, K.D., Bunting, M.J. and Fossit, J.A. (1997). Long term vegetation change in the western and northern isles, Scotland. Botanical Journal of Scotland, **49**, 127-140.

Bennett, K.D. and Provan, J. (2008). What do we mean by 'refugia'? Quaternary Science Reviews, **27**, 2449-2455.

Bennett, K.D., Simonson, W.D. and Peglar, S. (1990). Fire and man in post-glacial woodlands of eastern England. Journal of Archaeological Science, **17**, 635-642.

Bennett, K.D., Whittington, G. and Edwards, K.J. (1995). Recent plant nomenclatural changes and pollen morphology in the british isles. Quaternary Newsletter, **73**, 1-5.

Bennett, M.R. and Boulton, G.S. (1993). A reinterpretation of Scottish ' hummocky moraine' and its significance for the deglaciation of the scottish highlands during the younger Dryas or Loch Lomond Stadial. Geological Magazine, **130**, 301-318.

Berglund, B.E., Deluca, T.H. and Zackrisson, O. (2004). Activated carbon amendments to soil alters nitrification rates in scots pine forests. Soil Biology and Biochemistry, **36**, 2067-2073.

Berglund, B.E., Gaillard, M.J., Bjorkman, L. and Persson, T. (2008). Long-term changes in floristic diversity in southern sweden: Palynological richness, vegetation dynamics and land-use. Vegetation History and Archaeobotany, **17**, 573-583.

Bergman, L.M., Passe, T., Olofson, A., Zackrisson, O., Hornberg, G., Hellberg, G. and Bohline, E. (2003). Isostatic land uplift and Mesolithic landscapes: Lake tilting, a key to the discovery of Mesolithic sites in the interior of northern Sweden. Journal of Archaeological Science, **30**, 1451-1458.

Binney, H.A. (1997). *Multi proxy investigations into pine history in northern Scotland.* Unpublished PhD thesis, University of Durham.

Binney, H.A., Waller, R.G.W., Bunting, M.J. and Armitage, R. (2005). The interpretation of fen carr pollen diagrams: The representation of the dry land vegetation. Review of Palaeobotany and Palynology, **134**, 197-218.

Birks, H.H. (1970). Studies in the vegetational history of Scotland: I. A pollen diagram from Abernethy forest, Inverness-shire. Journal of Ecology, **58**, 827-846.

Birks, H.H. (1972). Studies in the vegetational history of Scotland. III. A radiocarbon dated pollen diagram from Loch Maree, Ross and Cromarty. New Phytologist, **71**, 731-754.

Birks, H.H. (1975). Studies in the vegetation history of Scotland. IV. Pine stumps in Scottish blanket peats. Philosophical transactions of the Royal Society of London B, **270**, 181-223.

Birks, H.H. and Mathewes, R. (1978). Studies in the vegetational history of Scotland. V. late Devensian and early Flandrian pollen and macrofossil stratigraphy at Abernethy forest, Inverness-shire. New Phytologist, **80**, 455-484.

Birks, H.J.B. (1989). Holocene isochrone maps and patterns of tree spreading in the British Isles. Journal of Biogeography, **16**, 530-542.

Birks, H.J.B. and Line, J.M. (1992). The use of rarefaction analysis for estimating palynological richness from quaternary pollen-analytical data. The Holocene, **2**, 1-10.

Birks, H.J.B. and Madsen, B.J. (1979). Flandrian vegetational history of little Loch Roag, Isle of Lewis, Scotland. Journal of Ecology, **76**, 825-842.

Bjune, A.E. (2003). Holocene vegetation history and tree-line changes on a north-south transect crossing major climate gradients in southern Norway-evidence from pollen and plant macrofossils in lake sediments. Review of Palaeobotany and Palynology, **133**, 249-275.

Blackford, J.J. and Chambers, F.M. (1993). Determining the degree of peat decomposition for peat based palaeoclimatic studies. International Peat Journal, **5**, 7-24.

Blackford, J.J., Innes, J.B., Hatton, J.J. and Caseldine, C.J. (2006). Mid-Holocene environmental change at black ridge brook, Dartmoor, SW England: A new appraisal based on fungal spore analysis. Review of Palaeobotany and Palynology, **141**, 189-201.

Blackmore, S., Steinmann, J.A.J., Hoen, P.P. and Punt, W. (2003). The northwest European pollen flora, 65: Betulaceae and Corylaceae. Review of Palaeobotany and Palynology, (The Northwest European Pollen Flora, VIII,), **123**, 71-98.

Boettger, T., Hiller, A. and Krementski, K. (2003). Mid-Holocene warming in the northwest kola peninsula, Russia: Northern pine-limit movement and stable isotope evidence. The Holocene, **13**, 403-410.

Bohncke, S.J.P. (1988). Vegetation and habitation history of the Callanish area, Isle of Lewis, Scotland. *The Cultural Landscape past present and future* (eds. Birks HH, Birks HJB, Kaland PE and Moe D), pp. 445-461. University Press, Cambridge.

Bonan, G.B. and Shugart, H.H. (1989). Environmental factors and ecological processes in boreal forests. Annual Review of ecological systematics, **20**, 1-20.

Boyd, W.E. and Dickson, J.H. (1986). Patterns in the geographical distribution of the early Flandrian *Corylus* rise in southwest Scotland. New Phytologist, **102**, 615-623.

Bradshaw, R.H.W. (1981). Modern pollen-representation factors for woods in south-east England. The Journal of Ecology, **69**, 45-70.

Bradshaw, R.H.W. (1988). Spatially precise studies of forest dynamics. In *Vegetation History* (eds B. Huntly and T.I. Webb), pp. 725-751. Kluwer, The Hague.

Bridge, M.C., Haggart, B.A. and Lowe, J.J. (1990). The history and palaeoclimatic significance of *Pinus* sylvestris in blanket peats from Scotland. Journal of Ecology, **78**, 77-99.

Bronk Ramsey, C. (2005). Improving the resolution of radiocarbon dating by statistical analysis: **In** “The Bible and Radiocarbon Dating: Archaeology, Text and Science.,. Levy, T.E & Higham, T.F.G. (eds)”, pp 57-64, Equinox, London.

Broström, A., Sugita, S. and Gaillard, M.J. (2004). Pollen productivity estimates for the reconstruction of past vegetation cover in the cultural landscape of southern Sweden. The Holocene, **14**, 368-381.

Brown, A., Birks, H.J.B. and Thompson, D.B.A. (1993). A new biogeographical classification of the Scottish uplands. II. vegetation-environmental relationships. Journal of Ecology, **81**, 231-251.

Bruce, M.A. and Servant, S.M. (2003). Fire and pinewood ecology in Scotland: A summary of recent research at Glen Tanar estate, Aberdeenshire. Scottish Forestry, **57**, 33-38.

Buckland, P.C. and Edwards, K.J. (1984). The longevity of pastoral episodes of clearance activity in pollen diagrams: The role of post occupation grazing. Journal of Biogeography, **11**, 243-249.

Bunting, M.J. (2002). Detecting woodland remnants in cultural landscapes: Modern pollen deposition around small woodlands in northwest Scotland. The Holocene, **12**, 291-301.

Bunting, M.J. (2003). Pollen vegetation relationships in non-arboreal moorland taxa. Review of Palaeobotany and Palynology, **125**, 285-298.

Bunting, M.J., Gaillard, M.J., Sugita, S., Middleton, R. and Bostrom, A. (2004). Vegetation structure and pollen source area. The Holocene, **14**, 651-660.

Calcote, R. (1995). Pollen source area and pollen productivity evidence from forest hollows. Journal of Ecology, **83**, 591-602.

Calcote, R. (1998). Identifying forest stand types using pollen from forest hollows. The Holocene, **8**, 423-432.

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

Cayless, S. and Tipping, R. (2002). Data on mid-Holocene climatic, vegetation and anthropogenic interactions at Stanshiel Rig,southern Scotland. Vegetation History and Archaeobotany. **11**, 201-210.

Chambers, F.M. and Elliot, L. (1989). Spread and expansion of *Alnus* mill. in the British Isles: Timing, agencies and possible vectors. Journal of Biogeography, **16**, 541-550.

Charman, D.J. (1992). Blanket mire formation at the cross lochs, Sutherland, northern Scotland. Boreas, **21**, 53-72.

Charman, D.J. (1994). Late glacial and Holocene vegetation history of the flow country, northern Scotland. The New Phytologist, **127**, 155-168.

Charman, D.J., Barber, K.E., Blaauw, M., Langdon, P.G., Mauquoy, D., Daley, T.J., Hughes, P.D.M. and Karofeld, E. (2009). Climate drivers for peatland palaeoclimate records. Quaternary Science Reviews, **28**, 1811-1819.

Cheddadi, R., Vendramin, G.G., Litt, T., François, L., Kageyama, M., Lorentz, S., Laurenz S., De Beaulieu, J., Sadori, I, Jost, A and Lunt D. (2006). Imprints of glacial refugia in the modern genetic diversity of *Pinus sylvestris*. Global Ecology and Biogeography, **15**, 271-282.

Clarke, A. 2007. Three lithic scatters: Chest of Dee, Caochanan Ruadha and Carn Fiaclach Beag, Mar Lodge Estate, Scotland. Report for the National Trust for Scotland

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C. and Sejrup, H.P. Pattern and timing of retreat of the last British-Irish ice sheet. Quaternary Science Reviews, **In Press, Corrected Proof**.

Clark, J.S. (1988). Particle motion and the theory of charcoal analysis: Source area, transport, deposition, and sampling. Quaternary Research, **30**, 67-80.

Clarke, J.S. and Royall, P.D. (1993). Particle-size evidence for source areas of charcoal accumulation in late Holocene sediments of eastern north American lakes. Quaternary Research, **43**, 80-89.

Clark, R.L. (1984). Effects on charcoal of pollen preparation procedures. Pollen et spores, **26 3/4**, 559-576.

Clark, S.H.E. (2003). Insect faunas associated with the fossil remains of *Pinus sylvestris* L. in blanket peat from northeast Scotland. Scottish Geographical Journal, **119**, 39-52.

Clark, S.H.E. and Edwards, K.J. (2004). Elm bark beetle in Holocene peat deposits and the northwest european elm decline. Journal of Quaternary Science, **19**, 525-528.

Clifford, T. and MacKenzie, N. (2004). A complete native woodland inventory for Scotland: Development of costed options for a methodology. Report to Scottish Natural Heritage. pp97.

Crawford, R.M.M. (1997). Oceanicity and the ecological disadvantages of warm winters. Botanical Journal of Scotland, **49**, 205-221.

Crawford, R.M.M. (2008). *Plants at the margin: Ecological limits and climate change*. Cambridge University Press, Cambridge.

Cushing, E.J. (1967). Evidence for differential pollen preservation in late quaternary sediments in Minnesota. Review of Palaeobotany and Palynology, **4**, 87-101.

Dalton, C., Birks, H.J.B., Brooks, S.J., Cameron, N.G., Evershed, R.P., Peglar, S., Scott, J.A. and Thompson, R. (2005). A multi-proxy study of lake-development in response to catchment changes during the Holocene at Lochnagar, north-east Scotland. Palaeogeography, Palaeoclimatology, Palaeoecology, **221**, 175-201.

Davies, A.L. (2003a). Torran Beithe: Holocene history of a blanket peat landscape. *The Quaternary of Glen Affric and Kintail, field guide.* (ed. Tipping, R.), pp. 41-48. Quaternary Research Association, London.

Davies, A.L. (2003b). Carnach mor and Cambran: Woodland history and land use in alluviul settings. *The quaternary of Glen Affric and Kintail, field guide.* (ed. Tipping, R.), pp. 75-83. Quaternary Research Association, London.

Davies, A.L. and Tipping, R. (2004). Sensing small-scale human activity in the palaeoecological record: Fine spatial resolution pollen analyses from Glen Affric, northern Scotland. The Holocene, **14**, 233-245.

Davies, A.L. (2007). Upland agriculture and environmental risk: A new model of upland land-use based on high spatial-resolution palynological data from west Affric, NW Scotland. Journal of Archaeological Science, **34**, 2053-2063.

Davis, B.A.S., Brewer, S., Stevenson, A.C. and Guiot, J. (2003). The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews, **22**, 1701-1716.

Deluca, T.H., Nilsson, M.C. and Zackrisson, O. (2002). Nitrogen mineralization and phenol accumulation along a fire chronosequence in northern Sweden. Oecologia, **133**, 206-214.

Diaz, S., Hodgson, J.G., Thompson, K., Cabido, M., Cornelissen, J.H.C., Jalili, A., Montserrat-Marti, G., Grime, J.P., Zarrinkamar, F., Asri, Y., Band, S.R., Basconcelo, S., Castro-Diez, P., Funes, G. and Al, E. (2004). The plant traits that drive ecosystems: Evidence from three continents. Journal of vegetation science, **15**, 295-304.

Dickson, J.H. (1988). Postglacial pine stumps in central Scotland. Scottish Forestry, **42**, 192-199.

Dickson, J.H. (1993). Scottish woodlands: Their ancient past and precarious present. Scottish Forestry, **47**, 73-80.

Dixon, P. and Fraser, I. (2007) The Early Medieval Landscape, In: *In the shadow of Bennachie, a field archaeology of Donside*. pp80-100. RCAHMS and the Society of Antiquarians of Scotland, Edinburgh.

Dubois, A.D. and Ferguson, D.K. (1985). The climatic history of pine in the cairngorms based on radiocarbon dates and stable isotope analysis, with an account of the events leading up to its colonisation. Review of Palaeobotany and Palynology, **46**, 55-80.

Dubois, A.D. and Ferguson, D.K. (1988). Additional for the climatic history of pine in the cairngorms, Scotland, based on radiocarbon dates and tree ring D/H ratios. Review of Palaeobotany and Palynology, **52**, 181-185.

Dunwiddie, P.W. (1987). Macrofossil and pollen representation of coniferous trees in modern sediments from Washington. Ecology, **68**, 1-11.

Durno, S.E. (1956). Pollen analysis of peat deposits in Scotland. Scottish Geographical Magazine, **72**, 177-187.

Durno, S.E. (1957). Certain aspects of vegetational history in northeast Scotland. Scottish Geographical Magazine, **73**, 176-184.

Durno, S.E. (1958). Pollen analysis of peat deposits in eastern Sutherland and Caithness. Scottish Geographical Magazine, **74**, 127-165.

Durno, S.E. (1959). Pollen analysis of peat deposits in the eastern Grampians. Scottish Geographical Magazine, **75**, 102-111.

Durno, S.E. (1961). Evidence regarding the rate of peat growth. Journal of Ecology, **94**, 347-351.

Edwards, C. and Mason, W.L. (2006). Stand structure and dynamics of four native Scots pine (*Pinus sylvestris* L.) woodlands in northern Scotland. Forestry, **79**, 261-277.

Edwards, K.J. (1978). *Palaeoenvironmental and archaeological investigations in the Howe of Cromar, Grampian region, Scotland.* Unpublished PhD thesis, University of Aberdeen.

Edwards, K.J. (1983). Quaternary Palynology multiple profile studies and pollen variability. Progress in Physical Geography, **7**, 587-609.

Edwards, K.J. (1988). The hunter gatherer / agricultural transition and the pollen record in the British Isles. *The Cultural Landscape past present and future.* (eds. Birks H.H., Birks H.J.B. and Kaland P.E. and Moe D.), pp. 225-266. Cambridge University Press, Cambridge.

Edwards, K.J., Hirons, K.R. and Newell, P.J. (1991). The palaeoecological and prehistoric context of minerogenic layers in blanket peat: A study from loch Dee, southwest Scotland. The Holocene, **1**, 29-39.

Edwards, K.J. and Ralston, I. (1984). Postglacial hunter-gatherers and vegetational history in Scotland. Proceedings of the Society of Antiquaries of Scotland, **114**, 15-34.

Edwards, K.J. and Whittington, G. (2000). Multiple charcoal profiles in a Scottish lake: Taphonomy, fire ecology, human impact and inference. Palaeogeography, Palaeoclimatology, Palaeoecology, **164**, 67-86.

Edwards, K.J., Whittington, G. and Tipping, R. (2000). The incidence of microscopic charcoal in late glacial deposits. Palaeogeography, Palaeoclimatology, Palaeoecology, **164**, 247-262.

Elias, S.A. (2006). Quaternary beetle research: The state of the art. Quaternary Science Reviews, **25**, 1731-1737.

Everest, J. and Kubik, P. (2006). The deglaciation of eastern Scotland: Cosmogenic 10Be evidence for a late-glacial stillstand. Journal of Quaternary Science, **21**, 95-104.

Favre, E., Escarguel, G., Suc, J., Thévenod, G. and Thévenod, L. (2008). A contribution to deciphering the meaning of AP/NAP with respect to vegetation cover. Review of Palaeobotany and Palynology, **148**, 13-35.

Foss, P.J. and Doyle, G.J. (1988). A palynological study of the Irish Ericaceae and *Empetrum*. Pollen et spores, **30**, 151-178.

Fossit, J.A. (1994a). Modern pollen rain in the north west of the British Isles. The Holocene, **4**, 365-376.

Fossit, J.A. (1994b). Late glacial and Holocene vegetation history of western Donegal, Ireland. Biology and Environment: Proceedings of the Royal Irish Academy, **94B**, 1-31.

Fossit, J.A. (1996). Late quaternary vegetation history of the western isles of Scotland. New Phytologist, **132**, 171-196.

Froyd, C.A. (2005). Fossil stomata reveal early pine presence in Scotland: Implications for postglacial colonisation analyses. Ecology, **86**, 579-586.

Froyd, C.A. and Bennet, K.D. (2006). Long term ecology of native pinewood communities in east Glen Affric, Scotland. Forestry, **79**, 279-291.

Froyd, C.A. and Willis, K.J. (2008). Emerging issues in biodiversity and conservation management: The need for a palaeoecological perspective. Quaternary Science Reviews, **27**, 1723-1732.

Gaffney, V., Fitch, S. and Smith, D. (2009). *Europe's lost world: The rediscovery of Doggerland*, 2nd edn. Council for British Archaeology, York.

Gannon, A., Halliday, S., Sherrif, J. and Welfare, A. (2007). Neolithic and bronze age landscapes. In *In the shadow of Bennachie: a field archaeology of Donside*, pp. 45-78. RCAHMS and Society of Antiquarians of Scotland, Edinburgh.

Gear, A.J. (1989). *Holocene vegetation history and the palaeoecology of Pinus sylvestris in northern Scotland.* Unpublished PhD thesis, University of Durham.

Gear, A.J. and Huntley, B. (1991). Rapid changes in the range limits of Scots pine 4000 years ago. Science, **251**, 554-547.

Geary, B. and Gilbertson, D. (1997). Pollen taphonomy of trees in a windy climate: Northbay plantation, Barra, outer Hebrides. Scottish Geographical Magazine, **113**, 113-120.

Gervais, B.R. and MacDonald, G.M. (2001). Modern pollen and stomate deposition in lake surface sediments from across the tree-line on the Kola peninsula, Russia. Review of Palaeobotany and Palynology, **114**, 223-237.

Giesecke, T. (2005a). Moving front or population expansion: How did *Picea abies* (L.) karst. become frequent in central Sweden? Quaternary Science Reviews, **24**, 2495-2509.

Giesecke, T., Bjune, A.E., Chiverrell, R.C., Seppa, H. and Birks, H.J.B. (2008). Exploring Holocene continentality changes in Fennno-Scandia using present and past tree distributions. Quaternary Science Reviews, **27**, 1296-1308.

Gilbertson, D.D., Schwenninger, J., Kemp, R.A. and Rhodes, E.J. (1999). Sand-drift and soil formation along an exposed north Atlantic coastline: 14,000 years of diverse geomorphological, climatic and human impacts. Journal of Archaeological Science, **26**, 439-469.

Gillespie, M.R. (2003). *Geological constraints on landscape development in the cairngorms,* Edinburgh. edn. British Geological Survey, Edinburgh.

Gimingham, C.H. (1960). Biological flora of the British Isles: *Calluna vulgaris* (L.) hull. The Journal of Ecology, **48**, 455-483.

Gimingham, C.H. (2002). *The ecology, land use and conservation of the cairngorms.* Packard Publishing, Aberdeen.

Godwin, H. (1975). *The history of the British flora*. Cambridge University, Cambridge.

Golledge, N.R. (2010). Glaciation of Scotland during the younger Dryas Stadial: A review. Journal of Quaternary Science, **25**, 550-566.

Golledge, N.R., Hubbard, A. and Sugden, D.E. (2008). High-resolution numerical simulation of younger dryas glaciation in Scotland. Quaternary Science Reviews, **27**, 888-904.

Grace, J. (1997). The oceanic tree-line and the limit for tree growth in Scotland. Botanical Journal of Scotland, **49**, 223-236.

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

Gray, J. and Song, S.J. (1984). Climatic implications of the natural variations of D/H ratios in tree ring cellulose. Earth and Planetary Science Letters, **70**, 129-138.

Gregory, R.A., Murphy, E.M., Church, M.J., Edwards, K.J., Guttman, E.B. and Simpson, D.D.A. (2005). Archaeological evidence for the first Mesolithic occupation of the western isles of Scotland. The Holocene, **15**, 944-950.

Grime, J.P., Hodgson, J.G. and Hunt, R. (2007). *Comparative plant ecology*. Castlepoint Press, Dalbeatie.

Grimm, E.C. (1987). CONISS: A FORTRAN 77 programme for stratigraphically constrained cluster analysis by incremental sum of squares. Computer Geosciences, **13**, 13-35.

Grimm, E.C. (1991). *Tilia and TiliaGraph.* Illinois State University, Illinois, USA.

Hall, A.M. (1996). The paleic relief of the Cairngorm Mountains. Transactions of the Royal Society of Edinburgh: Earth Sciences, **85**, 253-273.

Hall, S.A. (1981). Deteriorated pollen grains and the interpretation of quaternary pollen diagrams. Review of Palaeobotany and Palynology, **32**, 193-206.

Hansen, B.C.S. (1995). Conifer stomate analysis as a palaeoecological tool: An example from the Hudson bay lowlands. Canadian Journal of Botany, **73**, 244-252.

Hättestrand, M., Jensen, C., Hallsdóttir, M. and Vorren, K.D. (2008). Modern pollen accumulation rates at the north-western fringe of the European boreal forest. Review of Palaeobotany and Palynology, **151**, 90-109.

Havinga, A.J. (1984). A 20-year experimental investigation into the differential corrosion susceptibility of pollen and spores in various soil types. Pollen et spores, **26**, 541-558.

Hicks, S. (2001). The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. Review of Palaeobotany and Palynology, **117**, 1-29.

Higuera, P.E., Peters, M.E., Brubaker, L.B. and Gavin, D.G. (2007). Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quaternary Science Reviews, **26**, 1790-1809.

Higuera, P.E., Sprugel, D.G. and Brubacker, L.B. (2005). Reconstructing fire regimes with charcoal from small-hollow sediments: A calibration with tree-ring records of fire. The Holocene, **15**, 238-251.

Hobbs, R.J., Mallik, A.U. and Gimingham, C.H. (1984). Studies on fire in Scottish heathland communities: III. vital attributes of the species. The Journal of Ecology, **72**, 963-976.

Hornberg, G., Bohlin, E., Hellberg, G., Bergman, L., Zackrisson, O., Olofson, A., Wallin, J.E., and Passe, T. (2004). Effects of Mesolithic hunter-gatherers on local vegetation in a non-uniform glacio-isostatic land uplift area, northern Sweden. Vegetation History and Archaeobotany, **15**, 13-26.

Hornberg, G., Wallin, J.E., Passe, T., Wardle, D.A. and Zackrisson, O. (2005). Holocene land uplift and its influence on fire history and ecosystem development in boreal Sweden. Journal of vegetation science, **15**, 171-180.

Huntley, B. (1994). Late Devensian and Holocene palaeoecology and palaeoenvironments of the Morrone Birkwoods, Aberdeenshire, Scotland. Journal of Quaternary Science, **9**, 311-336.

Huntley, B. (1996). Quaternary palaeoecology and ecology. Quaternary Science Reviews, **15**, 591-606.

Huntley, B. and Birks, H.J.B. (1983). *An atlas of past and present pollen maps for Europe: 0-13000 years ago*. Kluwer, The Hague.

Huntley, B., Daniell, J.R.G. and Allen, J.R.M. (1997). Scottish vegetation history: The highlands. Botanical Journal of Scotland, **49**, 163-175.

Huntley, B. and Webb III, T. (1988). Vegetation history. *Spatially precise studies of forest dynamics.* (ed. R.H.W. Bradshaw), pp. 725-751. Kluwer, The Hague.

Innes, J.B., Blackford, J.J. and IG, S. (2004). Testing the integrity of fine spatial resolution palaeoecological records: Micro-charcoal data from near-duplicate peat profiles from the north York moors, UK. Palaeogeography, Palaeoclimatology and Palaeoecology, **214**, 295-307.

Innes, J.B. and Simmons, I.G. (2000). Mid-Holocene charcoal stratigraphy, fire history and palaeoecology at north gill, north york moors, UK. Palaeogeography, Palaeoclimatology, Palaeoecology, **164**, 151-165.

Jackson, S.T. and Kearsley, J.B. (1998). Quantitative representation of local forest composition in forest floor pollen assemblages. Journal of Ecology, **77**, 405-490.

Jackson, S.T. and Wong, A. (1994). Using forest patchiness to determine pollen source areas of closed canopy pollen assemblages. Journal of Ecology, **82**, 89-99.

Jacobson, G.L. and Bradshaw, R.H.W. (1981). The selection of sites for vegetational studies. Quaternary Research, **16**, 80-96.

James, J.C., Grace, J. and Hoad, S.P. (1994). Growth and photosynthesis of *Pinus sylvestris* at its altitudinal limit in Scotland. The Journal of Ecology, **82**, 297-306.

Jensen, C., Vorren, K.D. and M¢rkved, B. (2007). Annual pollen accumulation rate (PAR) at the boreal and alpine forest-line of north-western Norway, with special emphasis on *Pinus sylvestris* and *Betula pubescens*. Review of Palaeobotany and Palynology, **144,** 337-361.

Jessen,C.A, Rundgren,M., Bjork,S and Muscheler O (2007). Climate forced atmospheric CO2 variability in the early Holocene: A stomatal frequency reconstruction. Global and Planetary Change, **57**, 3, 247-260.

Jones, R.L. and Keene, D.H. (1993). *Pleistocene environments in the British Isles.* Chapman and Hall, London and New York.

Kaplan, J.O., Krumhardt, K.M. and Zimmermann, N. (2009). The prehistoric and preindustrial deforestation of europe. Quaternary Science Reviews, **28**, 3016-3034.

Kinloch, B.N.B., Westfall, R.D. and Forrest, G. (1986). Caledonian Scots pine: Origin and genetic structure. New Phytologist, **116**, 715-727.

Kobashi, T., Severinghaus, J.P., Brook, E.J., Barnola, J.M. and Grachev, A.M. (2007). Precise timing and characterization of abrupt climate change 8200 years ago from air trapped in polar ice. Quaternary Science Reviews, **26**, 1212-1222.

Koff, T., Punning, J.M. and Kangur, M. (2000). Impact of forest disturbance on the pollen influx in lake sediments during the last century. Review of Palaeobotany and Palynology, **111**, 19-29.

Korhola, A., Ruppel, M., Seppa, H., Veliranta, M., Virtanen, T. and Weckstrom, J. (2010). The importance of northern peatland expansion to the late-Holocene rise of atmospheric methane. Quaternary Science Reviews, **29**, 611-617.

Kremenetski, K.V., MacDonald, G.M., Gervais, B.R., Borisova, O.K. and Snyder, J.A. (2004). Holocene vegetation history and climate change on the northern Kola peninsula, Russia: A case study from a small tundra lake. Quaternary International, **122**, 57-68.

Kullman, L. (1988). Holocene history of the forest-alpine tundra ecotone in the Scandes mountains (central Sweden). New Phytologist, **108**, 101-110.

Kullman, L. (1995). Holocene tree-limit and climate history from the Scandes mountains, Sweden. Ecology, **76**, 2490-2502.

Kullman, L. (2008). Early postglacial appearance of tree species in northern Scandinavia: Review and perspective. Quaternary Science Reviews, **27**, 2467-2472.

Kullman, L. and Kjallgren, L. (2000). A coherent postglacial tree-limit chronology (*Pinus* sylvestris L.) for the Swedish Scandes: Aspects of palaeoclimate and "recent warming," based on megafossil evidence. Arctic, Antarctic and Alpine Research, **32**, 419-428.

Kultti, S., Mikkola, K., Virtanenj, T., Timonen, M. and Eronen M. (2006). Past changes in the Scots pine forest line and climate in Finnish Lapland: A study based on megafossils, lake sediments, and GIS-based vegetation and climate data. The Holocene, **16**, 381-391.

Landeweert, R., Hoffland, E., Finlay, R.D., Kuyper, T.W. and von Breeman, N. (2001). Linking plants to rocks: Ectomycorrhizal fungi mobilise nutrients from minerals. Trends in Ecology and Evolution, **16**, 248-253.

Langdon, P.G., Barber, K.E. and Hughes, P.D.M. (2003). A 7500-year peat-based palaeoclimatic reconstruction and evidence for an 1100-year cyclicity in bog surface wetness from temple hill moss, Pentland hills, southeast Scotland. Quaternary Science Reviews, **22**, 259-274.

Langdon, P.G. and Barber, K.E. (2005). The climate of Scotland over the last 5000 years inferred from multiproxy peatland records: Inter-site correlations and regional variability. Journal of Quaternary Science, **20**, 549-566.

Lanner, R.M. (1998). Seed dispersal in *Pinus*, In *Ecology and biogeography of Pinus.* (ed. Richardson D.M.), pp. 281-295. Cambridge University Press, Cambridge.

Ledig, F.T. (1998). Genetic variation in *Pinus*. *Ecology and biogeography of Pinus* (ed. Richardson D.M.), pp. 251-280. Cambridge University Press, Cambridge.

Lewis, F.J. (1906). The plant remains in the Scottish peat mosses, part II, the Scottish highlands. Transactions of the Royal Society of Edinburgh, **45**, 335-359.

Lewis, F.J. (1907). The plant remains in the Scottish peat mosses, part III the Scottish highlands and Shetland Islands. Transactions of the Royal Society of Edinburgh, **46**, 33-70.

Lewis, F.J. (1911). The plant remains in the Scottish peat mosses. IV. The Scottish highlands and Shetland, with an appendix on the Icelandic peat deposits. Transactions of the Royal Society of Edinburgh, **47**, 793-833.

Lowe, J.J. (1982a). Three Flandrian pollen profiles from the Teith valley, Perthshire, Scotland. I. Vegetational history. New Phytologist, **90**, 355-370.

Lowe, J.J. (1982b). Three Flandrian pollen profiles from the Teith valley, Perthshire, Scotland. II. Analysis of deteriorated pollen. New Phytologist, **90**, 371-385.

Lowe, J.J. and Walker, M.J.C. (1977). The reconstruction of the Lateglacial environment in the southern and eastern Grampian highlands. *Studies in the Scottish Late Glacial environment* (ed. Gray JM and Lowe JJ). Pergamon, Oxford.

Lyell, C. (1856). *The principles of geology: Or the modern changes of the earth and its inhabitants*, 10th edn. John Murray, London.

MacDonald, D. (2003). *Modelling the sub-Devonian land surface in NE Scotland: Implications for long-term denudation of highland Scotland*, Edinburgh edn. British Geological Survey, Edinburgh.

MacDonald, G.M., Beilman, D.W., Kremenetski, K.V., Sheng, Y., Smith, L.C. and Velicho, A.A. (2006). Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. Science, **314**, 285-288.

Malmer, N., Svensson, B.M. and Wallén, B. (1994). Interactions between *Sphagnum* mosses and field layer vascular plants in the development of peat-forming systems. Folia Geobotanica, **29**, 483-496.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Krefeld, S., Holmgren, K., Thorp, J.L., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R. and Steig, E.J. (2004). Holocene climate variability. Quaternary Research, **62, 3**, 243-255.

Mazier, F., Galop, D., Brun, C. and Buttler, A. (2006). Modern pollen assemblages from grazed vegetation in the western Pyrenees, France: A numerical tool for more precise reconstruction of past cultural landscapes. The Holocene, **16**, 91-103.

McClatchey, J. (1996). Spatial and altitudinal gradients of climate in the cairngorms-observations from climatological and automatic weather stations. Botanical Journal of Scotland, **48**, 31-49.

McConnel, J. and Legg, C. (1994). Are the upland heaths in the cairngorms pining for change? The Botanical Journal of Scotland, Special edition: The Cairngorms, **48**, 155-161.

McVean, D.N. (1955a). Ecology of *Alnus glutinosa* (L.) gaertn.: I. Fruit formation. Journal of Ecology, **43**, 46-60.

McVean, D.N. (1955b). Ecology of *Alnus glutinosa* (L.) gaertn.: II. Seed distribution and germination. Journal of Ecology, **43**, 61-71.

McVean, D.N. (1963a). Growth and mineral nutrition of Scots pine seedlings on some common peat types. Journal of Ecology, **51**, 657-670.

McVean, D.N. (1963b). The ecology of the Scots pine in the Scottish highlands. Journal of Ecology, **51**, 671-686.

McVean, D.N. and Ratcliffe, D.A. (1962). *Monographs of the nature conservancy: Plant communities of the Scottish highlands*. HMSO, London.

Mikola, P. (1962). Temperature and tree growth near the northern timber line. *Tree growth.* (ed. T.T. Kozlowski), pp. 265-274, New York.

Mitchell, F.J.G. (1990). The impact of grazing and human disturbance on the dynamics of woodland in S.W. Ireland. Journal of Vegetation Science, **1**, 245-254.

Mitchell, F.J.G. (2005). How open were European primeval forests? Hypothesis testing using palaeoecological data. Journal of Ecology, **93**, 168-177.

Moir, A.K., Brown, L.D. and Collins, P.E.F. (2010). Dendrochronological evidence for a lower water-table on peatland around 3200-3000 BC from sub-fossil pine in northern Scotland. The Holocene, **20**, 931-942.

Moore, J.R., Norman, D.B. and Upchurch, P. (2007). Assessing relative abundances in fossil assemblages. Palaeogeography, Palaeoclimatology, Palaeoecology, **253**, 317-322.

Moore, P.D., Webb, J.A. and Collinson, M.E. (1991). *Pollen analysis.* Blackwell Scientific Publishing, London.

Nesje, A., Bjune, A.E., Bakke, J., Dahl, S.O., Lie, ¥. and Birks, H.J.B. (2006). Holocene palaeoclimate reconstructions at Vanndalsvatnet, western Norway, with particular reference to the 8200 cal. yr BP event. The Holocene, **16**, 717-729.

Nilsson, M.C. and Wardle, D.A. (2005). Understory vegetation as a forest ecosystem driver: Evidence from the northern Swedish boreal forest. Frontiers of Ecological the Environment, **3**, 421-428.

Ordnance Survey 2011. Edina: http://digimap.edina.ac.uk/osmapper.

Ordnance Survey 2010. Edina: http://digimap.edina.ac.uk/geologymapper.

O'Sullivan, P.E. (1974a). Two Flandrian pollen diagrams from the east-central highlands of Scotland. Pollen et spores, **16**, 33-57.

O'Sullivan, P.E. (1974b). Radiocarbon dating and pre-historic forest clearance on Speyside (east central highlands). Proceedings of the Prehistoric Society, **40**, 206-208.

O'Sullivan, P.E. (1976). Pollen analysis and radiocarbon dating of a core from Loch Pityoulish, eastern highlands of Scotland. Journal of Biogeography, **3**, 293-302.

Parker, A.G., Goudie, A.S., Anderson, D.E., Robinson, M.A. and Bonsall, C. (2002). A review of the mid-Holocene elm decline in the British Isles. Progress in Physical Geography, **26**, 1-45.

Parshall, T. (1999). Documenting forest stand invasion: Fossil stomata and pollen in forest hollows. Canadian Journal of Botany, **77**, 1529-1538.

Parsons, R.W. and Prentice, I.C. (1981) Statistical approaches to R-values and the pollen-vegetation relationship. Review of Palaeobotany and Palynology. **32**, 127–52

Pears, N.V. (1968). Post glacial tree-lines of the Cairngorm Mountains Scotland. Transactions of the Botanical Society of Edinburgh, **40**, 361-394.

Pears, N.V. (1970a). Man in the cairngorms: A population resource balance problem. Scottish Geographical Magazine, **86**, 50-52.

Pears, N.V. (1970b). Post-glacial tree-lines of the Cairngorm Mountains, Scotland: Some modifications based on radiocarbon dating. Transactions of the Botanical Society of Edinburgh, **40**, 536-544.

Pears, N.V. (1988). Pine stumps, radiocarbon dates and stable isotope analysis in the Cairngorm Mountains: Some observations. Review of Palaeobotany and Palynology, **52**, 175-185.

Pennington, W., Haworth, E.Y., Bonny, A.P. and Lishman, J.P. (1972). Lake sediments in northern Scotland. Philosophical transactions of the Royal Society of London, B Biological Sciences, **264**, 191-294.

Peterkin, G.F. (2001). Ecological effects of introduced species in Britain. Forest Ecology and Management, **141**, 31-42.

Peters, M.E. and Higuera, P.E. (2007). Quantifying the source area of macroscopic charcoal with a particle dispersal model. Quaternary Research, **67**, 304-310.

Philips, W.M., Hall, A.M., Mottram, R., Fifield, L.K. and Sugden, D.E. (2006). Cosmogenic ^{10}Be and ^{26}Al exposure ages of tors and erratics, cairngorm mountains, Scotland: Timescales for the development of a classic landscape of selective linear glacial erosion. Geomorphology, **73**, 222-245.

Pielou, E.C. (1979). *Biogeography*. Wiley, New York and Chichester.

Pratt, S. (2006a). *Long-term landscape dynamics in a Caledonian pine forest.* Unpublished PhD thesis, University of Edinburgh.

Pratt, S. (2006b). Reconstructing past landscapes at abernethy forest: Some new insights from palaeoecology and pollen modelling. Scottish Woodland Discussion Group, **15**.

Prentice, I.C. (1981). Quantitative birch (*Betula* L.) pollen separation by analysis of size frequency data. New Phytologist, **89**, 145-157.

Prentice, I.C. (1988). Records of vegetation in time and space: The principles of pollen analysis. *Vegetation History* (ed. Huntly, B. and Webb, T. III), pp. 17-42. Kluwer, The Hague.

Prentice, I.C. and Webb III, T. (1986). Pollen percentages, tree abundance and the Fagerlind effect. Journal of Quaternary Science, **1**, 35-43.

Preston, C.D., Pearman, D.A. and Dines, T.D. (2002). *New atlas of the British and Irish flora*. Oxford University Press, Oxford.

Punt, W., Marks, A. and Hoen, P.P. (2002). The northwest European pollen flora, 66, Myricaceae. Review of Palaeobotany and Palynology (The Northwest European Pollen Flora, VIII,), **123**, 99-105.

Quine, C.P. (2003). Wind as a forest disturbance agent - and its implications for forest landscape patterns at Glen Affric. In, *The potential of applied landscape ecology to forest design planning,* (ed. S. Bell), pp. 1-55. Forestry Commission, Edinburgh.

Rackham, O. (2001). *The history of the countryside.* Phoenix Press, London.

Ramsay, S. and Dickson, J.H. (1997). Vegetational history of central Scotland. Botanical Journal of Scotland, **49**, 141-150.

Rapson, S.C. (1985). Minimum age of corrie moraine ridges in the cairngorm mountains, Scotland. Boreas, **14**, 155-159.

Dixon, P., Green, S.T., Stevenson J.B. and Mercer, R.J.1995. Mar Lodge Estate, Grampian: an archaeological survey. Royal Commission on Ancient and Historic Monuments (RCAHMS), Edinburgh, pp40.

Read, D.J., Leake, J.R. and Perez-Moreno, J. (2004). Mycorrhizal fungi as drivers of ecosystem processes in heathland and boreal forest biomes. Canadian Journal of Botany, **82**, 1243-1263.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Edward, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J. and Weyhenmeyer, C.E. (2004). Intcal04 terrestrial radiocarbon age calibration 0-26cal KYR BP. Radiocarbon, **46**, 1029-1058.

Richardson D.M. and Rundel P.W. (1998). Ecology and biogeography of *Pinus*: An introduction. *Ecology and Biogeography of Pinus.* (ed. Richardson D.M.), pp. 3-46. Cambridge University Press, Cambridge, UK.

Ritchie, J.C. (1956). *Vaccinium myrtillis* L. The Journal of Ecology, **44**, 291-299.

Rodwell, J.S. (1991). *(1991) British plant communities volume 1: Woodlands and scrub.*Cambridge University Press, Cambridge.

Sagoff, M. (1999). *What's wrong with exotic species?* Institute for Philosophy and Public policy, report no.34, p43-48.

Samuelsson, G. (1910). Scottish peat mosses. Bulletin of the Geological Society of Uppsala, **10**, 197-260.

Schwartz, M.W. (1989). Predicting tree frequencies from pollen frequency: An attempt to validate the R-value method. New Phytologist, **112**, 120-143.

Scott, A.C., Cripps, J.A., Collinson, M.E. and Nichols, G.J. (2000). The taphonomy of charcoal following a recent heathland fire and some implications for the interpretation of fossil charcoal deposits. Palaeogeography, Palaeoclimatology, Palaeoecology, **164**, 1-31.

Seppä, H. (1998). Postglacial trends in palynological richness in the northern Fennno-Scandia tree-line area and their ecological interpretation. The Holocene, **8**, 43-53.

Seppä, H. and Bennett, K.D. (2003). Quaternary pollen analysis: Recent progress in Palaeoecology and Palaeoclimatology. Progress in Physical Geography, **27**, 548-579.

Seppä, H. and Birks, H.J.B. (2002). Holocene climate reconstructions from the Fenno-Scandia tree-line area based on pollen data from Toskaljavri. Quaternary Research, **57**, 191-199.

Seppä, H. and Hicks, S. (2006). Integration of modern and past pollen accumulation rate (PAR) records across the arctic tree-line: A method for more precise vegetation reconstructions. Quaternary Science Reviews, **25**, 1501-1516.

Seppä, H., MacDonald, G.M., Birks, H.J.B., Gervais, B.R. and Snyder, J.A. (2008). Late-quaternary summer temperature changes in the northern-european tree-line region. Quaternary Research, **69**, 404-412.

Shaw, H. (2006). *A palaeoecological investigation of long term stand scale ecological dynamics in semi-open native pine woods: Contributing to conservation management in east Glen Affric.* Unpublished PhD thesis, University of Stirling.

Simmons, I.G. (1996). *The environmental impact of later Mesolithic cultures; the creation of the moorland landscape of England and Wales*. Edinburgh University Press, Edinburgh.

Simmons, I.G. and Innes, J.B. (1996a). Disturbance phases in the mid-Holocene vegetation at north gill, north York moors: Form and process. Journal of Archaeological Science, **23**, 183-191.

Simmons, I.G. and Innes, J.B. (1996b). Prehistoric charcoal in peat profiles at north gill, north Yorkshire moors, England. Journal of Archaeological Science, **23**, 193-197.

Simmons, I.G. and Innes, J.B. (1996c). An episode of prehistoric canopy manipulation at north gill, north Yorkshire, England. Journal of Archaeological Science, **23**, 337-341.

Sinclair, W.T., Norman, J.D. and Ennos, R.A. (1998). Multiple origins for Scots pine (*Pinus sylvestris* L) in Scotland: Evidence from mitochondrial DNA variation. Heredity, **80**, 233-240.

Sissons, J.B. (1979). The Loch Lomond advance in the cairngorm mountains. Scottish Geographical Journal, **95**, 66-82.

Sjögren, P., van der Knaap, W.O., Huusko, A. and van Leeuwen, J.F.N. (2008). Pollen productivity, dispersal, and correction factors for major tree taxa in the swiss alps based on pollen-trap results. Review of Palaeobotany and Palynology, **152**, 200-210.

Skene, K.R., Sprent, J.L., Raven, J.A. and Herdman, L. (2000). Biological flora of the British Isles: *Myrica gale* L. Journal of Ecology, **88**, 1079-1094.

Smith A.G. and Pilcher J.R. (1973). Radiocarbon dates and vegetational history of the British Isles. New Phytologist, **72**, 4, 903-914.

Smith, J.M.B. (1978). Dispersal and establishment in plants. *Biology and Quaternary Environments* (ed. Walker D and Guppy JC), pp. 207-225. Australian Academy of Science, Canberra.

Smout, T.C. (1997). Highland land-use before 1800: Misconceptions, evidence and realities. *Scottish Forestry History* (ed. Smout TC), pp. 5-23. Scottish Cultural Press, Aberdeen.

Soepboer, W. and Lotter, A.F. (2009). Estimating past vegetation openness using pollen vegetation relationships: A modelling approach. Review of Palaeobotany and Palynology, **153**, 102-107.

Stace, C. (1991). *New flora of the British Isles*. Cambridge University Press, Cambridge.

Steven, H.M. and Carlisle, A. (1959). *The native pinewoods of Scotland*. Oliver and Boyd, Edinburgh.

Stockmarr, J. (1977). Tablets with spores used in absolute pollen analysis. Pollen *et* Spores, **13**, 615-621.

Sugita, S. (1993). A model of pollen source area for an entire lake surface. Quaternary Research, **39**, 239-244.

Sugita, S. (1994). Pollen representation of vegetation in quaternary sediments: Theory and method in patchy vegetation. Journal of Ecology, **82**, 881-897.

Sugita, S., Gaillard, M.J. and Bostrom, A. (1999). Landscape open-ness and pollen records: A simulation approach. The Holocene, **9**, 409-421.

Sugita, S. (2007a). Theory of quantitative reconstruction of vegetation. I. pollen from large sites REVEALS regional vegetation. The Holocene., **17**, 229-241.

Sweeney, C.A. (2004). A key for identification of stomata of the native conifers of Scandinavia. Review of Palaeobotany and Palynology, **128**, 281-290.

Tallantire, P.A. (2002). The early-Holocene spread of hazel (*Corylus avellana* L.) in Europe north and west of the Alps: An ecological hypothesis. The Holocene, **12**, 81-96.

Tallis, J.H. (1991). Forest and moorland in the south Pennine uplands in the mid-Flandrian period: III. The spread of moorland- local, regional and national. Journal of Ecology, **79**, 401-415.

Tallis, J.H. (1997). The pollen record of *Empetrum nigrum* in southern Pennine peats: Implications for erosion and climate change. Journal of Ecology, **85**, 455-465.

Tang, K., Feng, X. and Ettl, G.J. (2000). The variations in % δD of tree rings and the implications for climatic reconstruction. Geochimica et Cosmochimica Acta, **64**, 1663-1673.

Tauber, H. (1965). Differential pollen dispersion and the interpretation of pollen diagrams. Danmarks Geologiske Undersoegelse (Ajhandlinger), **89**, 1-69.

Thomas, C.W., Gillespie, M.R., Jordan, C. and Hall, A.M. (2004). *Geological structure and landscape of the Cairngorm Mountains. commissioned report number 064. ROAME no F00AC103*. Scottish Natural Heritage.

Tinner, W., Nielsen, E.H. and Lotter, A.F. (2007). Mesolithic agriculture in Switzerland? A critical review of the evidence. Quaternary Science Reviews, **26**, 1416-1431.

Tipping, R. (1987). The origins of corroded pollen grains at five early postglacial pollen sites in western Scotland. Review of Palaeobotany and Palynology, **53**, 151-161.

Tipping, R. (1994). The form and fate of Scotland's woodlands. Proceedings of the Society of Antiquarians of Scotland, **124**, 1-54.

Tipping, R. (1996). Microscopic charcoal records, inferred human activity and climate change in the Mesolithic of northernmost Scotland. *The early prehistory of Scotland.* (eds. A. Pollard and A. Morrison), pp. 39-61. Edinburgh University Press, Edinburgh.

Tipping, R. (2000). Pollen preservation analysis as a necessity in Holocene pollen analysis. *Taphonomy and Interpretation.* (eds. S. Stallybrass and J.P. Huntley), pp. 23-34. Oxbow, Oxford.

Tipping, R. (2002). Climatic variability and marginal settlement in British upland landscapes: A re-evaluation. Landscapes, **3**, 10-28.

Tipping, R. (2003). Living in the past: Woods and people in prehistory to 1000BC. *People and woods in Scotland.* (ed. Smout, T.C.), pp. 14-39. Edinburgh University Press, Edinburgh.

Tipping, R. (2007). Landscape evolution and environmental history of the don valley and north east Scotland. In *In the shadow of Bennachie: a field archaeology of Donside.* RCAHMS and Society of Antiquaries of Scotland.

Tipping, R. (2008a). Blanket peat in the Scottish highlands: Timing, cause, spread and the myth of environmental determinism. Biodiversity Conservation, **17**, 2097-2113.

Tipping, R. (2008b). Storminess as an explanation for the decline of pine woodland ca. 7,400 years ago at loch tulla, western Scotland. Vegetation History and Archaeobotany, 12, 211-221.

Tipping, R. (2010). The case for climatic stress forcing choice in the adoption of agriculture in the British Isles. *Landscapes in Transition* (eds. B. Finlayson and G. Warrena), pp. 66-77. Oxbow Books.

Tipping, R., Ashmore, P., Davies, A.L., Haggart, B.A., Moir, A., Newton, A., Sands, R., Skinner, T. and Tisdall, E. (2008). Prehistoric *Pinus* woodland dynamics in an upland landscape in northern Scotland: The roles of climate change and human impact. Vegetation History and Archaeobotany, **17**, 251-267.

Tipping, R., Davies, A.L., Reid, E. and Tisdall, E. (2003). Late quaternary landscape evolution of Glen Affric and Kintail. *The quaternary of Glen Affric and Kintail: field guide* (ed. Tipping RM), pp. 9-27. Quaternary Research Association, London.

Tipping, R. and Milburn, P. (2000). Mid Holocene charcoal fall in southern Scotland- temporal and spatial variability. Palaeogeography, Palaeoclimatology, Palaeoecology, **164**, 177-193.

Tipping, R., Tisdall, E. and Davies, A.L. (2003). Peat development in west Glen Affric. *The Quaternary of Glen Affric and Kintail field guide.* (ed. Tipping, R.), pp. 49-54. Quaternary Research Association, London.

Tisdall, E. (2003). West Glen Affric: Peat stratigraphic data on Holocene climate change- humification patterns and the identification of a long term temperature record. *The quaternary of Glen Affric and Kintail: field guide* (ed. Tipping, R.M.), pp. 55-62. Quaternary Research Association, London.

Trautmann, W. (1953). Zur unterscheidung fossiller spaltoffnungen der mitteleuropaischen coniferen. Flora, 54, 523-533.

Traverse, A. (1988). *Palaeopalynology*. Springer-Verlag.

United Kingdom Meteorological Office (2011). *Braemar weather records 1885-present.*, http://www.metoffice.gov.uk/climate/uk/stationdata edn. United Kingdom Meteorological Office.

vad Odgaard, B. (1999). Fossil pollen as a record of past biodiversity. Journal of Biogeography, **26**, 7-17.

van Geel, B. (1978). A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands, based on the analysis of pollen, spores and macro- and microscopic remains of fungi, algae, cormophytes and animals. Review of Palaeobotany and Palynology, **25**, 1-120.

Vasari, Y. and Vasari, A. (1968). Late and post-glacial macrophytic vegetation in the lochs of northern Scotland. Acta Botanica Fennica, **80**, 1-120.

von Stedingk, H., Fyfe, R.M. and Allard, A. (2008). Pollen productivity estimates from the forest--tundra ecotone in west-central Sweden: Implications for vegetation reconstruction at the limits of the boreal forest. The Holocene, **18**, 323-332.

Walker, M.J.C. and Lowe, J.J. (1981). Postglacial environmental history of Rannoch moor, Scotland. III. Early and mid Flandrian stratigraphic data from sites on western Rannoch moor and near Fort William. Journal of Biogeography, **8**, 475-491.

Walker, M.J.C. and Lowe, J.J. (1997). Vegetation and climate in Scotland 13000 to 7000 radiocarbon years ago. *Reflections on the Ice Age in Scotland - an Update on Quaternary Studies* (ed. J.E. Gordon). Scottish Association of Geography, Glasgow.

Ward, R.G.W., Haggart, B.A. and Bridge, M.C. (1987). Dendrochronological studies of bog pine from the Rannoch Moor area, western Scotland. *Applications of Tree ring studies* (ed. Ward RGW). British Archaeological Reports, International Series 333.

Wardle, D.A., Bardgett, R.D., Klironomos, J.N., Setala, H., van der Putten, W.h. and Wall, D. (2005). Ecological linkages between above ground and below ground biota. Science, **304**, 1629-1633.

Wardle, D.A., Hornberg, G., Zackrisson, O., Kalela-Brundin, M. and Coomes, D.A. (2003). Long term effects of wildfire on ecosystem properties across an island area gradient. Science, **300**, 972-975.

Wardle, D.A., Walker, L.R. and Bardgett, R.D. (2004). Ecosystem properties and forest decline in contrasting long-term chronosequences. American Association for the Advancement of Science, 61, 45-60.

Wardle, D.A., Zackrisson, O., Gallet, C. and Hornberg, G. (1997). The influence of island area on ecosystem properties. Science, **277**, 1296-1299.

Watson, A. (1983). Eighteenth century deer numbers and pine regeneration near Braemar, Scotland. Biological Conservation, **25**, 289-305.

Watson, J. (1984). The ending of the Caledonian orogeny in Scotland. Journal of the Geological Society, **141**, 193-214.

Watt, A.S. and Jones, E.W. (1948). The ecology of the cairngorms. I. The environment and altitude of the vegetation. Journal of Ecology, **36**, 283-304.

Whitehouse, N.J. (2006). The Holocene British and Irish ancient forest fossil beetle fauna: Implications for forest history, biodiversity and faunal colonisation. Quaternary Science Reviews, **25**, 1755-1789.

Whitehouse, N. J and Smith, D (2010). How fragmented was the British Holocene wildwood? Perspectives on the "Vera" grazing debate from the fossil beetle record. Quaternary Science Reviews, **29**, 3-4, 539-553.

Wilkins, D.A. (1984). The Flandrian woods of Lewis, Scotland. The Journal of Ecology, **72**, 251-258.

Willis, K.J., Bennett, K.D. and Birks, H.J.B. (1998). The late quaternary dynamics of pines in Europe. *Ecology and Biogeography of Pinus* (ed. Richardson DM), pp. 107-121. Cambridge University Press, Cambridge.

Wilmshurst, J.M. and McGlone, M.S. (2005). Origin of pollen and spores in surface lake sediments: Comparison of modern palynomorph assemblages in moss cushions, surface soils and surface lake sediments. Review of Palaeobotany and Palynology, **136**, 1-15.

Yapp, C.J. and Epstein, S. (1982). A re-examination of cellulose carbon-bound hydrogen δD measurements and some factors affecting plant water D/H relationships. Geochimica et Cosmochimica Acta, **46**, 955-965.

Yellof, D. and Mauquoy, D. (2006). The influence of vegetation composition on peat humification: Implications for palaeoclimatic studies. Boreas, **35**, 662-673.

Zackrisson, O., Deluca, T.H., Nilsson, M.C., Sellstedt, A. and Berglund, B.E. (2004). Nitrogen fixation increases with successional age in boreal forests. Ecology, **85,** 3327-3334.

Zackrisson, O., Nilsson, M.C., Steijlen, I. and Hornberg, G. (1995). Regeneration pulses and climate-vegetation interactions in non-pyrogenic boreal Scots pine stands. The Journal of Ecology, **83**, 469-483.

Zackrisson, O., Nilsson, M.C. and Wardle, D.A. (1996). Key ecological functions of charcoal from wildfire in boreal forest. Oikos, **77**, 10-19.

Appendix

Pollen percentage, concentration and influx diagrams and charcoal ratios from Doire Bhraghad, White Bridge and Geldie Lodge

Figure A.1a Doire Bhraghad percentage pollen diagram all taxa

Figure A.1b Doire Bhraghad pollen concentration diagram

Figure A.1c Doire Bhraghad pollen influx diagram

Figure A.1d Doire Bhraghad, charcoal percentages, charcoal ratios and summary percentage pollen diagram

Figure A.2a White Bridge percentage pollen diagram all taxa

Figure A.2b White Bridge pollen concentration diagram

Figure A.2c White Bridge pollen influx diagram

Figure A.2d White Bridge, charcoal percentages, charcoal ratios and summary percentage pollen diagram

Figure A.3a Geldie Lodge percentage pollen diagram all taxa

Figure A.3b Geldie Lodge pollen concentration diagram

Figure A.3c Geldie Lodge pollen influx diagram

Figure A.3d Geldie Lodge, charcoal percentages, charcoal ratios and summary percentage pollen diagram

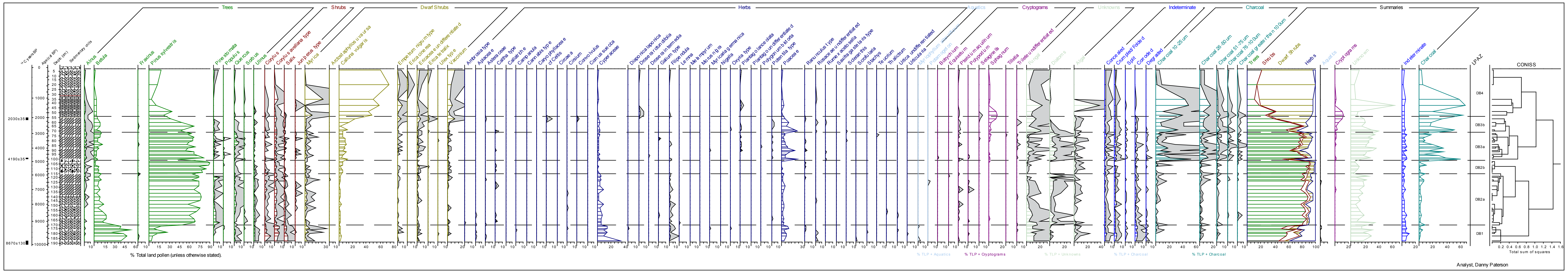


Figure A.1a. Doire Bhraghad percentage pollen diagram all taxa

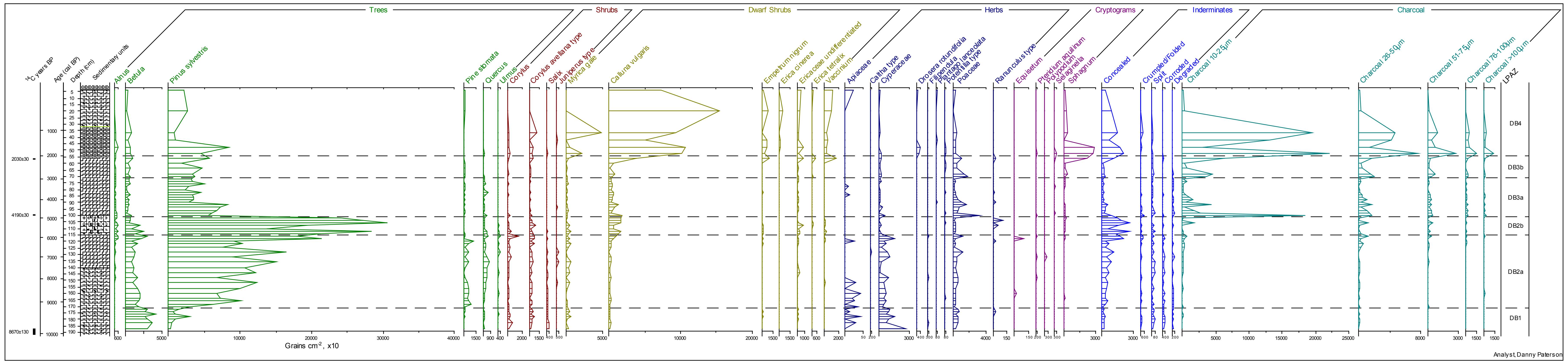


Figure A.1b. Doire Bhraghad, pollen concentration diagram

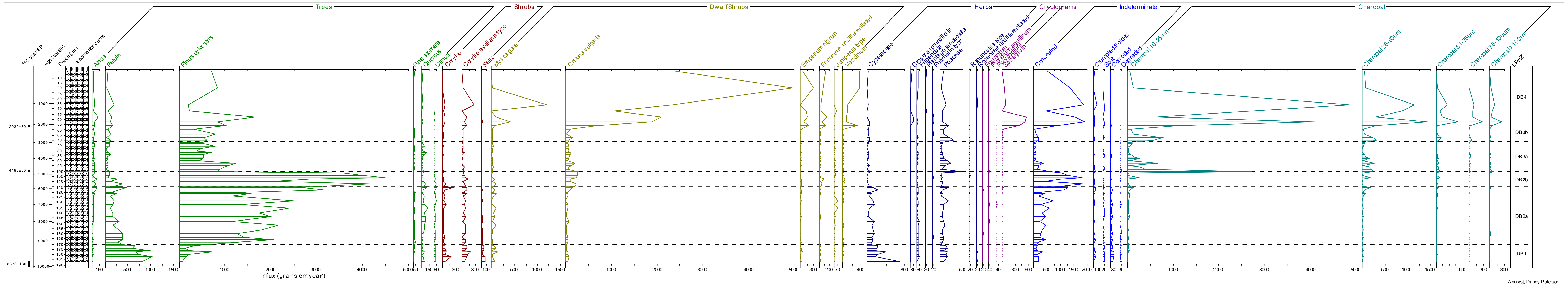
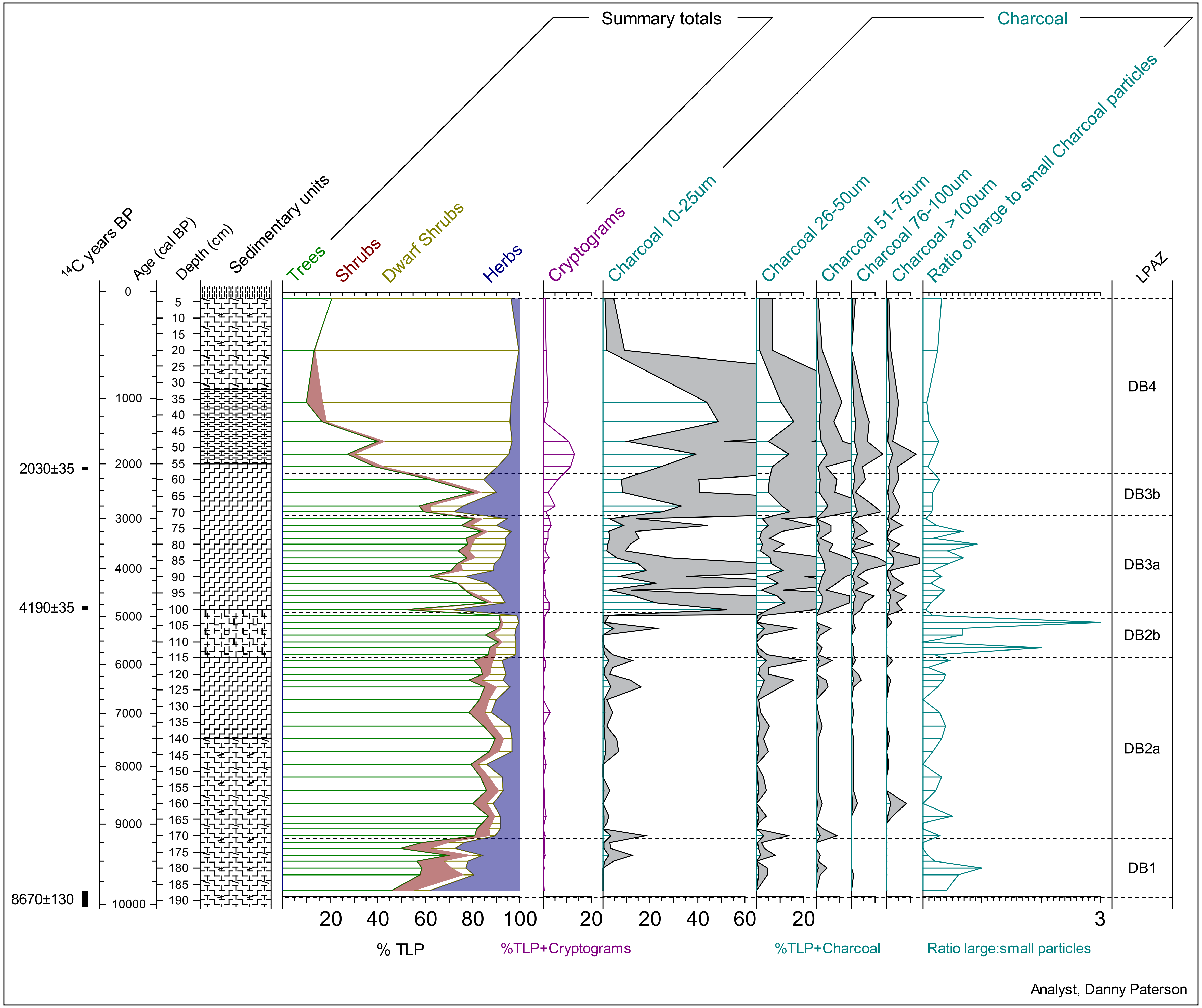


Figure A.1c. Doire Bhraghad, pollen influx diagram


Summary totals
Charcoal
¹⁴C years BP
Age (cal BP)
Depth (cm)
Sedimentary units
Trees
Shrubs
Dwarf Shrubs
Herbs
Cryptograms
Charcoal 10-25um
Charcoal 26-50um
Charcoal 51-75um
Charcoal 76-100um
Charcoal >100um
Ratio of large to small Charcoal particles
LPAZ
2030±35
4190±35
8670±130
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
DB4
DB3b
DB3a
DB2b
DB2a
DB1
20
40
60
80
100
20
20
40
60
20
3
% TLP
%TLP+Cryptograms
%TLP+Charcoal
Ratio large:small particles
Analyst, Danny Paterson

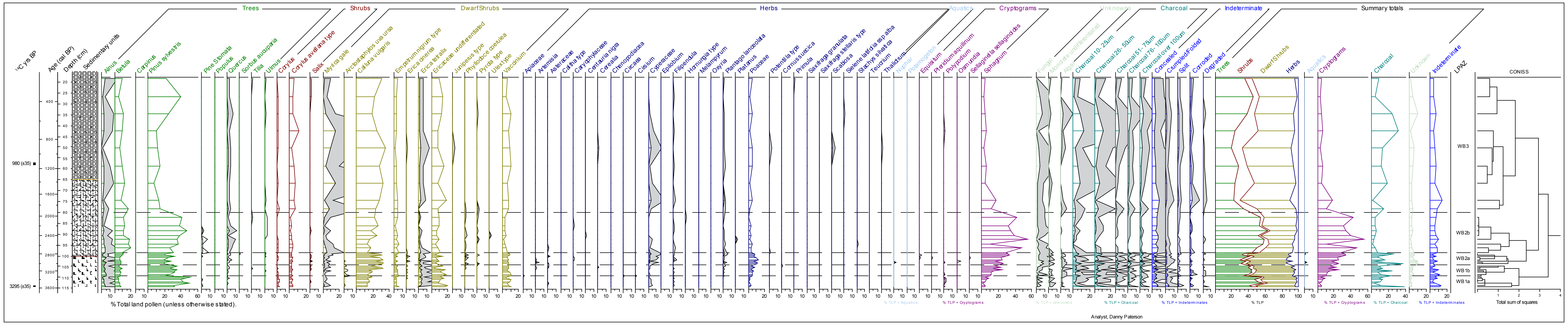


Figure A.2a. White Bridge percentage pollen diagram, all taxa

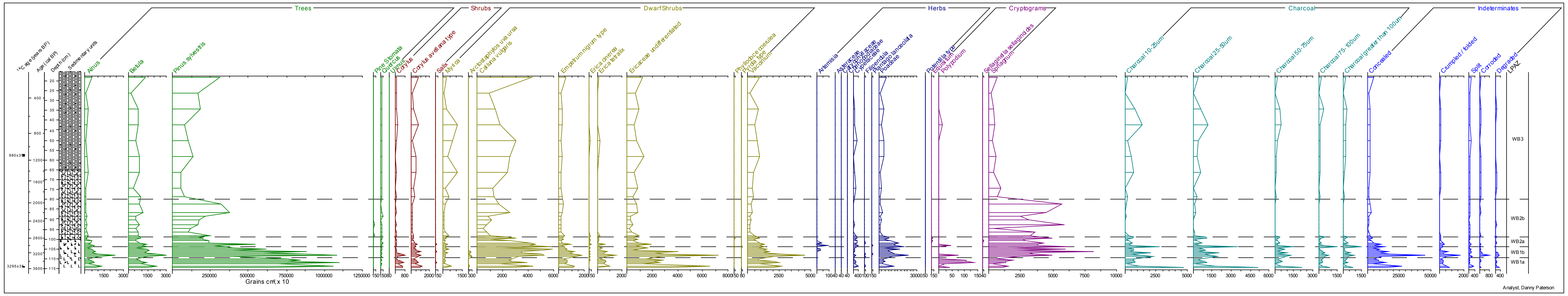


Figure A.2b. White Bridge, pollen concentration diagram

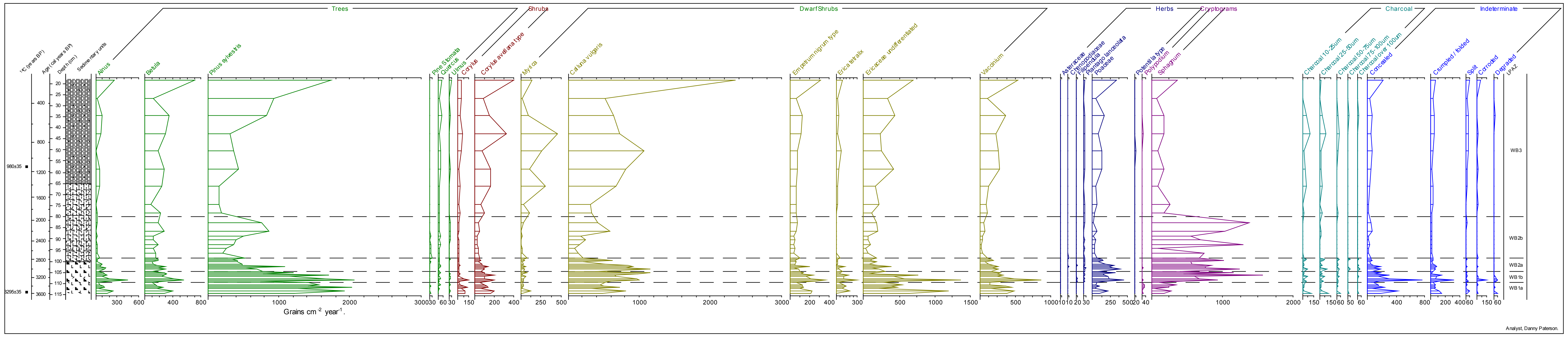
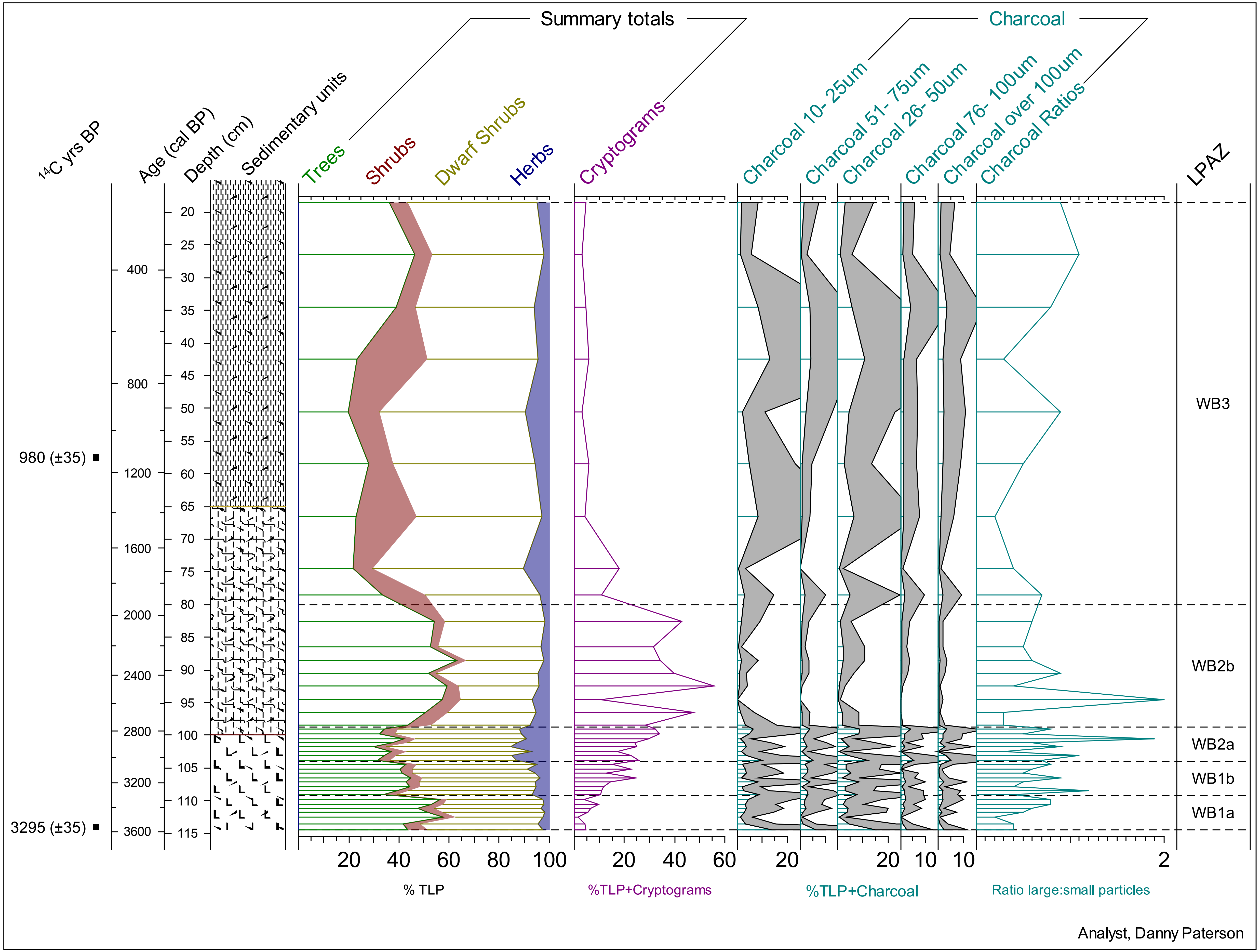


Figure A.2c. White Bridge, pollen influx diagram


Summary totals
Charcoal
14C yrs BP
Age (cal BP)
Depth (cm)
Sedimentary units
Trees
Shrubs
Dwarf Shrubs
Herbs
Cryptograms
Charcoal 10- 25um
Charcoal 51- 75um
Charcoal 26- 50um
Charcoal 76- 100um
Charcoal over 100um
Charcoal Ratios
LPAZ
980 (±35)
3295 (±35)
400
800
1200
1600
2000
2400
2800
3200
3600
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
WB3
WB2b
WB2a
WB1b
WB1a
20 40 60 80 100
% TLP
20 40 60
%TLP+Cryptograms
20 20 10 10
%TLP+Charcoal
2
Ratio large:small particles
Analyst, Danny Paterson

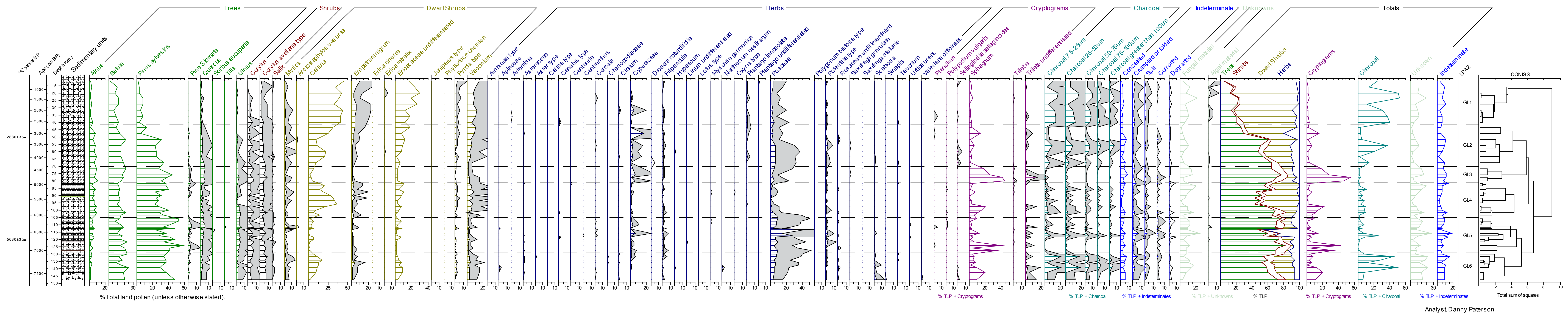


Figure A.3a. Geldie Lodge percentage pollen diagram, all taxa

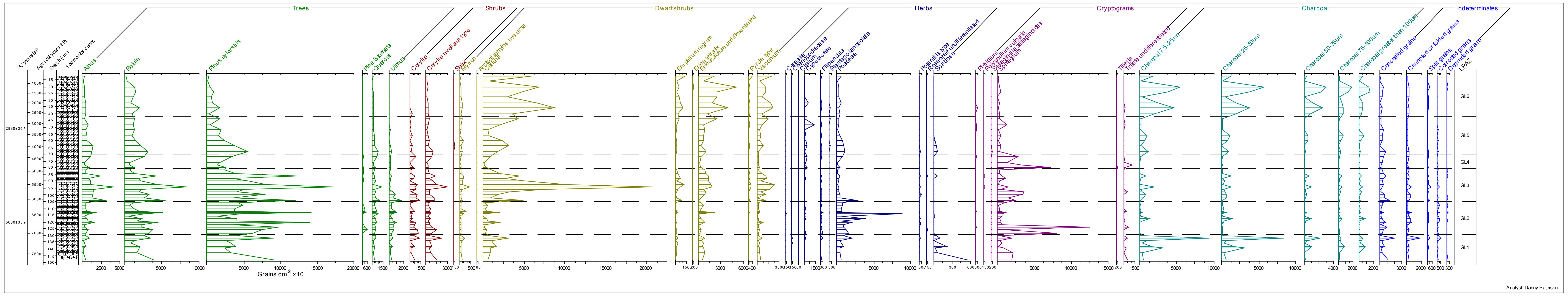


Figure A.3b. Geldie Lodge, pollen concentration diagram

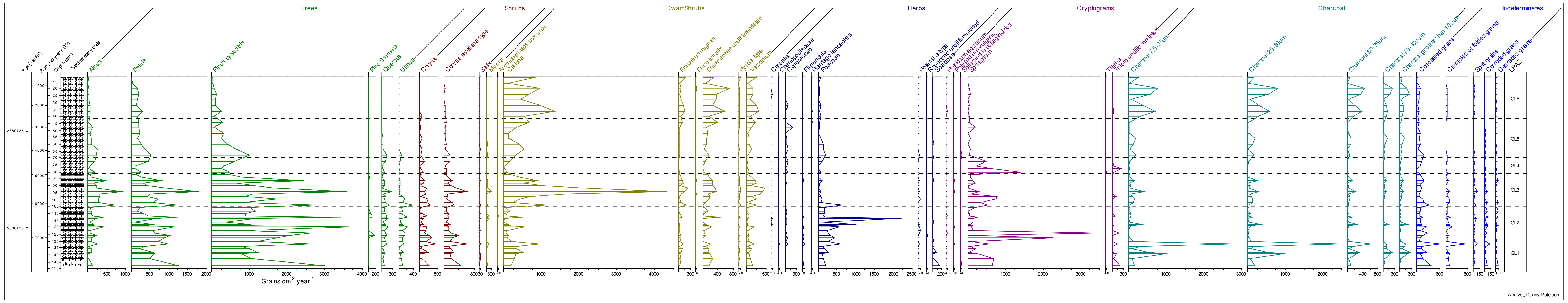
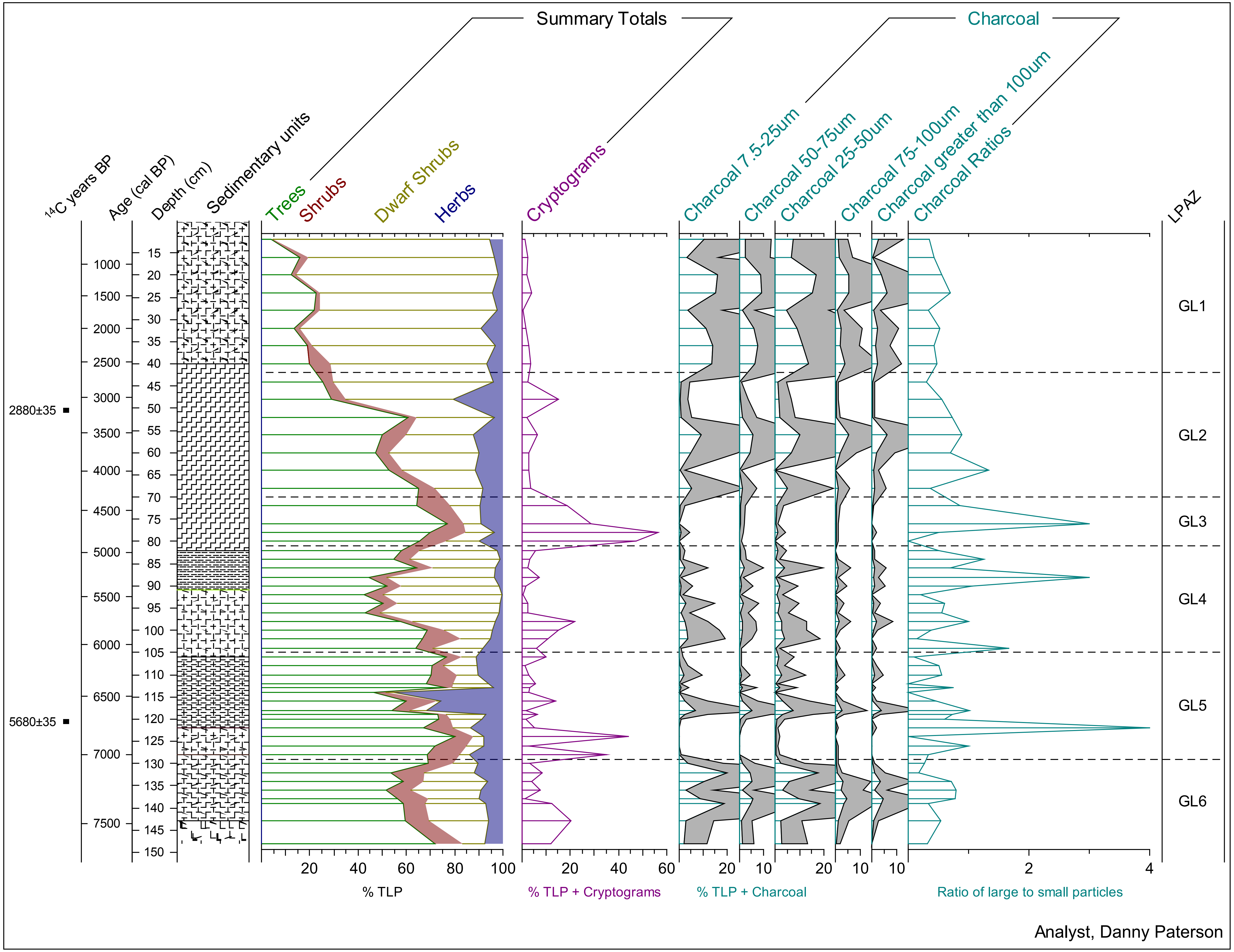


Figure A.3c. Geldie Lodge, pollen influx diagram


Summary Totals
Charcoal
^{14}C years BP
Age (cal BP)
Depth (cm)
Sedimentary units
Trees
Shrubs
Dwarf Shrubs
Herbs
Cryptograms
Charcoal 7.5-25um
Charcoal 50-75um
Charcoal 25-50um
Charcoal 75-100um
Charcoal greater than 100um
Charcoal Ratios
LPAZ
2880±35
5680±35
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
20 40 60 80 100
% TLP
20 40 60
% TLP + Cryptograms
20 10 20 10 10
% TLP + Charcoal
2 4
Ratio of large to small particles
GL1
GL2
GL3
GL4
GL5
GL6
Analyst, Danny Paterson