UNIVERSITY OF LIVERPOOL

Department of Geography

PhD Thesis

Holocene stand-scale forest dynamics of the British Isles

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor of Philosophy

By

Claire S. Jones

Department of Geography
The University of Liverpool
Roxby building
Liverpool
L69 7ZT, U.K.

Declaration

I hereby declare that all of the work contained within this dissertation has not been submitted for any other qualification.

Signed: C. D. Jones

Date: 20/04/2011

Abstract

The work presented in this thesis investigates the changing vegetation structure and dynamics at two sites of specific interest to the ecological, palaeoecological and public communities. Wistman's Wood, Dartmoor, UK, thought to be a rare relict example of an upland oakwood and is one of only three on upland Dartmoor. The second site, Cleddon Bog, is believed to be a deteriorating wood-pasture system in the Wye Valley, UK. The second section of the thesis studies fire as a disturbance mechanism across the British Isles through the Holocene. It attempts to differentiate between the three major drivers of fire: climate, vegetation and human activities.

Quercus is the dominant tree species in Wistman's Wood and its dominance is the cause of much speculation. The high species diversity and presence of atlantic brypophytes are thought to be an indication of ancient woodland. The use of pollen and charcoal analysis of a mor humus core spanning almost 2000 years BP, was collected from within the present canopy attempts to investigate the past structure of the woodland, establishing that the woodland is indeed ancient. Results of palaeoecological analysis also indicate that ~2000years ago the woodland was much more diverse than present, containing *Quercus*, *Alnus*, *Betula* and *Fraxinus*. It also appears likely that disturbance prior to the 19th century resulted in an opening of the woodland and a loss of species diversity, with *Quercus* dominance developing in the late 19th century.

Pollen and charcoal analysis of a 1.27 metre core spanning ~8000 years BP from Cleddon Bog was used to address questions regarding the origins of the wood-pasture system and potentially identify solutions for management due to a change in vegatation structure in the recent past. Results confirmed that woodland had been present at the site for almost 8000 years. A diverse woodland was recorded until 3000 years BP, composed of *Alnus*, *Betula*, *Pinus*, *Quercus*, *Ulmus* and *Corylus*. More open conditions occurred ~3000 years BP with *Poaceae*, *Cyperaceae* and *Calluna vulgaris*, along with some arboreal pollen. The continuity of woodland at the site is likely to have resulted in the present high species diversity of the bog

To address the question of natural or anthropogenic fire during the Holocene and to assess its role as a disturbance mechanism, a collection of 57 charcoal records from across the British Isles were compiled. The data were analysed in terms of the spatio-temporal and pollen-vegetation relationships. Pollen-inferred vegetation characteristics are used to identify possible links between fuel characteristics and fire frequency, along with cultural indicators in the pollen record which are used to explore human influence upon the fire regime. The charcoal record is variable throughout the Holocene, with most abundant values during the last 3000 years. There are significant correlations between the fire record and *Calluna*, *Plantago lanceolata* and Poaceae. These analyses have confirmed that it is difficult to distinguish between the drivers of palaeoefire, however it is likely that the fire regime of the past 3000 years was strongly influenced by human activity and climatic factors were probably of greater significance during the early Holocene.

Acknowledgements

I would first like to extend my thanks to my supervisor Prof. Richard Bradshaw for giving me the opportunity to work with him, and for providing support and guidance throughout the project. Thanks also to my secondary supervisor Dr. Fabienne Marret for our impromptu conversations regarding the thesis. Advice on site selection came from Dr. George Peterken and Dr. Edward Mountford and the Forestry Commission for permission to core at these sites. The studentship was sponsored jointly by The Network of Excellence EVOLTREE, European Commission 6th Framework Programme and Department of Geography, University of Liverpool. Thanks also to the NERC radiocarbon dating laboratory, East Kilbride, for the preparation and production of the radiocarbon dates, especially Dr Mark Garnett and Dr Steve Moreton. Funding was provided by the NERC radiocarbon steering committee.

Working in the Department of Geography has been a great experience and could not have been so if it were not for the people who work there. The departmental lecturing staff have been a source of experience and fun, there are so many to name that it would not be possible in this acknowledgements, but I would specifically like to thank Prof. Andy Plater for the taxing, but hilarious Christmas quiz. I would like to thank all of the postgraduates in the department, past and present, without their continued banter and sharing of common thoughts, my experience would not have been so enjoyable. I would particularly like to thank Dr. Lee Bradley, Dr. Ian Thrasher, Dr. Katharine Welsh, Dr. 'Mary' Ningning Li, Jenifer Clear, Hayley Mills, Karen Halsall, David Clarke and Timothy Shaw with whom I have had many a laugh and a moan, thank you for your support! My thanks also go to Mette Overballe-Petersen for many a conversation via email and discussions at conferences!

Without the support of the technical and administrative staff within the department, this research would not have been possible. They are always happy to help, know exactly what it is you need to do (when it comes to form filling and those other things that just get in the way!). I would especially like to thank Irene Cooper, Hilda Hull and Alan Henderson for their help and advice with laboratory work. Jayne Avies, Claire Rimmer and Andrea Wall for their friendly greetings and advice with all things administrative. Also thanks go to, Sandra Mather, Suzanne Yee, Tinho Da Cruz and Robert Hunt.

I would really like to thank my friends who have supported me throughout the past four years, by providing me with a kind ear, a glass of wine and a laugh. Gemma Lancaster, Stephanie Smith, Sarah Lowthorpe, Kate Webster, Gail and Dr. Kenneth Edwards, thank you so much, without your friendship I would never have got here! Thanks also to my co-workers at Envirolink Northwest, for their understanding and support, especially Jackie Seddon, Lisa Campbell and Paul Theodore.

Finally, I would like to thank my family. My Mum and Dad for their continued unwavering confidence in me. Their help and support throughout, whether it be proof reading, shopping or fixing things that go wrong! To my brother Michael for the chatting and pampering. My Uncle for his humour and fabulous presents! To my Nan for her kindness and encouragement. Also, my thanks go to the Williams family, Jan, Keith, Adam, Frances, Gladys and Phil, you have been a source of encouragement. Whilst on the topic of family, I have to mention our dog Maxwell,...thanks for providing me with excuses to go for walks, hours of fun and not eating my thesis!

Last, but by no means least my partner Craig, who is also my partner in PhD madness! Thank you so much for your love, friendship, encouragement, support, motivation, when I needed it most and confidence, when I had none. You have made these PhD years so much more enjoyable!

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation for research

British forests are important contact points between people and nature and a major focus of their management is to protect and enhance their biodiversity and their natural values (DEFRA 2002). There are continuing efforts to restore and preserve semi-natural woodlands in the British Isles (UK Biodiversity Action Plan 2010). Development of appropriate management strategies raises both theoretical and practical issues regarding the species of preservation value and the dynamics of the past vegetation. This project focuses on forest structure and composition, which are two key determinants of biodiversity and natural value (Honnay *et al.* 2004). It is hoped that the project will help to develop practical guidelines for appropriate management of semi-natural forests in two typical British landscapes. The project therefore addresses a specific research issue related to the long-term maintenance and enhancement of forest biodiversity and has relevance for the issue of the impacts of long-term climatic change on forest ecosystems

Stand-scale palynology is a palaeoecological technique that has been used in Scandinavia (Bradshaw 1993, Björkman and Bradshaw 1996) and North America (Bradshaw and Webb 1985; Calcote 1995) to investigate past vegetation structure at a stand-scale and vegetation dynamics in the past. Previous application of this technique in the British Isles has been limited, Ireland (Bradshaw and Hannon 1988; Mitchell 1988, 1990a, 1990b), Wales (Edwards 1986) and England (Bradshaw 1981; Day 1993). This research extends the range of sites and forms the most recent work using small forest hollows in the British Isles.

There are significant debates throughout north-west Europe regarding the structure, composition and disturbance mechanisms active in the mid- to late-Holocene woodlands of lowland north-west Europe (Vera 2000, Mitchell 2005, and Bradshaw *et al.* 2003, Birks 2005). Stand-scale investigation of this matter within the British Isles will inform this debate. Assessment of disturbance mechanisms active within British Isles will also provide information regarding the merits of both the wood pasture and high forest hypothesis. The wood pasture hypothesis proposing that during the early Holocene large herbivores contributed to the maintenance of open conditions in lowland woodlands, discerned from palynological investigations. The long-standing high forest hypothesis proposes that, prior to human disturbance the primeval forests were dominated by high, closed canopy and mixed communities of deciduous trees.

Fire is an important disturbance mechanism in the Earth system, affecting a variety of ecosystems (Marlon *et al.* 2008). Our knowledge of past fire regimes is developing all the time, however more work is needed to truly assess the regional relationships between burning, climatic changes, vegetation patterns and anthropogenic activities. The present view of fire within the British landscape is of burning being of anthropogenic cause (Peterken 1996, Moore 2000). However the potential for natural ignition of British vegetation may have been underestimated.

1.2 Thesis Aim and Objectives

The primary aim of the work presented was to investigate the stand-scale forest dynamics active within the woodlands of the British Isles, using stand-scale palynology and to use the information obtained to inform the active scientific debate regarding forest openness and contribute to management plans for investigated sites. The specific objectives of the research were to:

- Use stand-scale palynology to investigate the long-term vegetation structure at two Sites of Special Scientific Interest (S.S.S.I) in the British

Isles. These included an ancient woodland, Wistman's Wood and a degraded wood-pasture, Cleddon Bog.

- Identify the forest structures and native species associated with specific sites in the past.
- Characterise fire as a disturbance mechanism in the British Isles by compiling a database of charcoal records and mapping these records across space and time.

1.3 Thesis Structure and Overview

The thesis is divided into six chapters which detail the methods used to investigate the changing compositions of two sites in the British Isles and the development and analysis of the British Isles Charcoal Database (BICD). It begins with this introductory chapter, outlining the thesis aim and objectives. This is then followed by Chapter 2, which presents a review of background literature and current knowledge. Chapter 2 gives details of the current debates regarding forest structure in the mid-Holocene, namely the 'wood-pasture hypothesis' and the 'high forest hypothesis'. A review of current knowledge regarding natural disturbance mechanisms in forests is also presented. Finally, a review of current methods used to investigate forest dynamics is presented, including pollen analysis, charcoal analysis and stand-scale palynology.

Chapter 3 presents a stand-scale palynological investigation of Wistman's Wood, Dartmoor, thought to be ancient woodland. In the chapter the current knowledge of the vegetation structure of the woodland is presented. Methods used by the author to investigate the past vegetation composition are outlined. Results of the palynological investigation are summarised and along with details regarding past vegetation structure. In particular the origins of oak (*Quercus*) dominance within this woodland, one of three oak-dominated woodlands that remain on Dartmoor are discussed.

The work in Chapter 4 details a palynological investigation into a deteriorating wood-pasture system, Cleddon Bog, Wye Valley. A review of historical knowledge of the wider Wyeswood area is presented. Details of the methodology used are outlined. The work details the changing vegetation structure of the area throughout the mid- to late-Holocene and investigates the potential for fire as an agent for the development of the wood-pasture system.

Chapter 5 investigates the aspects of fire as a disturbance mechanism in the British Isles during the Holocene. The criteria and methods used to collate charcoal records from across the British Isles are detailed. Analytical methods used to map charcoal both temporally and spatially are also outlined, and finally the comparison of the charcoal record with pollen data from sites. Results of temporal and spatial mapping of these charcoal records are presented, along with results of comparisons of the charcoal record with the vegetative record.

Finally, Chapter 6 outlines conclusions drawn from the presented research, along with recommendations for further and future investigation.

1.4 References

Birks, H.J.B. (2005) Mind the gap: how open were European primeval forests?, *Trends in Ecology and Evolution*, **20**, 4, 154-156.

Björkman, L., Bradshaw, R.H.W. (1996) The immigration of Fagus sylvatica L. and Picea abies (L.) Karst into a natural forest stand in southern Sweden during the last 2000 years, *Journal of Biogeography*, **23**, 235-244.

Bradshaw, R.H.W. (1981) Quantitative reconstruction of local woodland vegetation using pollen analysis from a small basin in Norfolk, England, *Journal of Ecology*, **69**, 941-955.

Bradshaw, R.H.W., Hannon, G.E. (1988) Human influence in the decline of the Irish forest ecosystem, In Salbitano, F. (eds) *Human influence on forest ecosystems development in Europe*, ESF FERN-CNR, Pitagora Editrices, Bologna, 21-30.

Bradshaw, R.H.W., Webb, T. (III) (1990) Relationships Between Contemporary Pollen and Vegetation Data from Wisconsin and Michigan, USA, *Ecology*, **66**, 721-737.

Bradshaw, R.H.W. (1993) Tree species dynamics and disturbance in three Swedish boreal forest stands during the last two thousand years, *Journal of Vegetation Science*, **4**, 6, 759-764.

Bradshaw, R.H.W., Hannon, G.E., Lister, A.M. (2003) A long-term perspective on ungulate-vegetation interactions, *Forest Ecology and Management*, **181**, 267-280.

Calcote, R. (1995) Pollen source area and pollen productivity: evidence from forest hollows, *Journal of Ecology*, **83**, 591-602.

Day, P. (1993) Woodland origine and ancient woodland indicators': a case-study from Sidlings Copse, Oxfordshire, UK, The Holocene, 3, 1, 45-53.

DEFRA (2002) Working with the grain of nature. A biodiversity strategy for England. DEFRA, London.

Edwards, M.E. (1986) Disturbance Histories of Four Snowdonian Woodlands and Their Relation to Atlantic Bryophyte Distributions, *Biological Conservation*, **37**, 301-320.

Honnay, O., Verheyen, K., Bossuyt, B. & Hermy, M. (2004) Forest biodiversity. Lessons from history for conservation, p. 285. CAB International, Wallingford.

Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., Prentice, I. C. (2008) Climate and human influences on global biomass burning over the past two millennia, *Nature Geoscience*, Vol. 1.

Mitchell, F.J.G. (1988) The Vegetational History of the Killarney Oakwoods, SW Ireland: Evidence from Fine Spatial Resolution Pollen Analysis, *Journal of Ecology*, **76**, 2, 415-436.

Mitchell, F.J.G. (1990a) The impact of Grazing and Human Disturbance on the Dynamics of Woodland in S.W. Ireland, *Journal of Vegetation Science*, **1**, 2, 245-254.

Mitchell, F.J.G. (1990b) The History and Vegetation Dynamics of a Yew Wood (Taxus baccata L.) in S.W. Ireland, *New Phytologist*, **115**, 3, 573-577.

Mitchell, F.J.G. (2005) How open were European primeval forests? Hypothesis testing using palaeoecological data, *Journal of Ecology*, **91**, 168-177.

Moore, J. (2000) Forest fire and human interaction in the early Holocene woodlands of Britain, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **164**, 125-137.

Peterken, G.F. (1996) *Natural Woodland*, Cambridge University Press, Cambridge.

UK Biodiversity Action Plan, available at http://www.ukbap.org.uk/ , accessed September 2010.

Vera, F. W. M. (2000) Grazing ecology and forest history, p. 506. CAB International, Wallingford.

Chapter 2

Literature Review

2.1 Introduction

This chapter documents a current state of the art review for the key topics and methods relevant to the results chapters in this thesis. Specifically these will cover disturbance mechanisms within natural forests and current theories regarding the vegetation structure and composition of the Holocene woodlands of the British Isles. Questions regarding conservation, management and status of sites were key determinants in the selection of sites for this research project and as a result a review of current work on the role of palaeoecology within the naturalness debate will be presented. A review of the role of palaeoecology in conservation management of woodlands will also be discussed. Definitions and background information regarding ancient woodland status is considered. Finally a review of the specific methodologies employed to conduct this research are present, including pollen analysis, charcoal analysis, dating and chronology and the use of stand-scale palynology.

2.2 Natural forest disturbance mechanisms

There are a number of definitions available to describe 'disturbance', 'disturbances are generally understood to be interruptions in a settled condition or interferences in the continuation of a state of process' (Peterken 1996, p. 87). The development of the definition has resulted in a more physical definition, which recognises disturbances at a range of spatial scales and on a variety of different levels of biological organisation, (Pickett and White 1985, White 1987). Further discussion of the topic resulted in alternative definitions, such as Oliver and Larsen's (1990) description in terms of vegetation structure, acknowledging that disturbances are events making growing spaces more available.

As a result of this array of definitions a variety of disturbance mechanisms can be identified, and in this section key mechanisms will be discussed, these include wind, fire, biotic (including large mammals and insects), ice and snow, landslips and other physical disturbances. Disturbances within forests at some point result in the opening of the forest canopy, these are referred to as 'gaps'. Within these gaps regeneration of species normally takes place at varying time-scales. Regeneration within forests has been the topic of much debate in recent years, with the high-forest hypothesis being challenged by the wood-pasture hypothesis(Vera 2000). These varying viewpoints will also be discussed.

The significance of gaps was recognised by Watt (1923-25) in studies within mature beechwoods. He noted that regeneration largely took place within gaps and that regeneration took place on differing time scales and composition was different, depending upon the gap size, condition of the canopy and coincidence between gap formation and most years. Gaps can be of any size, however generally are distinguished as small gaps, formed by the loss of individual trees or small groups, and large gaps formed as a result of a loss of a significant number of individuals, usually caused by a catastrophic disturbance (Peterken 1996).

The following describes the main natural disturbance mechanisms active within forest ecosystems. The effects of these disturbance mechanisms are easily identifiable with a forest over the life-time of an ecologist, however within the palaeorecord it is difficult to identify the exact causes of vegetation change. In general, stand-scale investigations can detect a change in canopy cover, i.e. closed canopy indicated by a dominance of arboreal pollen whereas a dominance of herbaceous and other open community taxa, indicates open canopy conditions. The cause of the change of structure is difficult to ascertain, however disturbances such as fire leave charcoal in the sedimentary record (Iversen 1941). It is also possible to use insect remains to determine species present in the woodland and potentially relate this information to changes in vegetation composition(Bradshaw and Zackrisson 1990). The use of fungal remains present in sediments such as peat, have also been shown to have palaeoecological significance (Van Geel 1986).

2.2.1 *Wind*

Wind is one of the most studied gap forming mechanisms due to its clearly delimited and easily identified events (Peterken 1996). In most temperate broad-leaved forests it is the main agent of disturbance. Wind can have a variety of effects upon forests, high winds can result in the uprooting of trees, splitting trunks and removal of branches. Impacts are greater on older trees, with full crowns and particularly trees in full leaf. Certain species are more susceptible to uprooting, those with shallow roots such as *Fagus*, whereas *Quercus*, a deep-rooted tree will likely remain standing, but shed crown branches (Peterken 1996). Quine (2003) considered that wind is the principal agent in the disturbance of British forests at present.

2.2.2 *Fire*

Peterken refers to this disturbance mechanism as 'unique' as it has the 'property of converting energy within vegetation into change of vegetation' (1996, p. 100). It is widely believed that broadleaved forests are relatively fire-resistent as they generally grow in moist habitats. Fire favours thick-barked mature trees such as Oak (*Quercus*). Conifer forests usually burn easily due to the drier habitats and resins within the trees. Some species are favoured by fire, either by having protective mechanisms (for example protection by inert bark), Pine (*Pinus*) and *Sequoia*, or by taking advantage of the creation of gaps by regenerating rapidly taking advantage of other less responsive competitors (Peterken 1996). Frequency and intensity of fires can influence the extent to which trees are affected, rapidly moving fires will often clear dead plant material on the forest floor, but barely touch the trees themselves.

2.2.3 Biotic disturbances

It is difficult to distinguish between the activities of micro-organisms, animals and plants which are components of the forest community and activities which in certain circumstances can be seen as a disturbance (Peterken 1996). Biotic disturbances include the action of large mammals, fungi and insects. Fungi are capable of creating small gaps in the forest canopy by killing individual mature trees or small groups. In recent years, there has been an outbreak of 'sudden oak death' in woodlands in the UK, which is caused by strains of *Phytophthora* fungus and is not limited to Oak (*Quercus*), but also included species such as Beech (*Fagus*) and Ash (*Fraxinus*) (Forestry Commission 2010a). It affects the tree by producing cankers on the trunk, dieback of foliage and eventually death. Insect infestation also has the potential to kill individual to large groups of trees. In the UK there are a variety of insect pests, with new ones being identified each year. These include the Oak processionary moth (*Thaumetopoea processionea*), Gypsy moth (*Lymantria dispar*) and Horse-chestnut leaf miner (*Cameraria ohridella*) (Forestry Commission 2010b). Management has been known to accentuate the effects of what would be a natural disturbance. Peterken (1996) describes how years of fire suppression in the Lodgepole pine forests of Yellowstone National Park, USA, helped the Mountain pine beetle (*Dendroctonus ponderosae*) to devastate old growth stands in the 1970's.

Finally, the effects of large mammals on natural forests can be significant. Their activities can range from the creation of small gaps to the destruction of large areas, for example the building of dams by beavers, creating pools of water which results in the death of flooded trees, creating open areas within the canopy. Sustained browsing can also result in the creation of gaps due to preference usually displayed towards seedlings and saplings, meaning that the competitive advantage is passed to the herb and shrub species (Peterken 1996). The effects of large herbivore browsing has been a topic of much discussion in recent years (Svenning 2002; Bradshaw *et al.* 2003; Mitchell 2005) after the proposal of the 'wood-pasture' or 'Vera' hypothesis by Frans Vera, a Dutch ecologist (2000). The outcomes of this debate will be discussed later.

2.2.4 *Drought*

Drought within a woodland refers to the severity and duration of water stress on a community of trees, it becomes a disturbance mechanism when the stress is so severe that canopy trees are killed or when subordinate trees are thinned out at an increased rate. Water stress is experienced when water intake to the tree is sufficiently low, that it is not sufficient to sustain normal process. Stress can be caused when temperature and the rate of evapo-transpiration are high, precipitation is low, or when uptake of water is prevented by frozen soil (Peterken 1996). Drought generally kills leaves prematurely, then branches and even whole trees. However generally a drought will cause a die-back within the forest (Peterken 1996). North temperate broad-leaved forests are generally more susceptible to drought if they grow on shallow soil, rock outcrops, are mid-elevation forests and on south-facing slopes (Clinton *et al.* 1993). In areas where drought is a recurring factor, species resistant to this stress will begin to dominate, selected from the local pool of species.

2.2.5 *Ice and Snow*

Large accumulations of snow and ice can be damaging to crown branches, generally resulting in weakened branches. Mature broadleaved trees with flat crowns are generally more susceptible, mature conifers are less so because of the shape of their crowns. Saplings of all species are affected, however when the snow melts they are generally able to recover.

2.2.6 *Wood-pasture versus high forest hypothesis*

There are currently two competing hypotheses regarding the structure and dynamics of lowland north western European woodlands during the mid Holocene, these are the high forest and wood-pasture hypotheses (Birks 2005). The traditional view is that presented in the high forest hypothesis (Iversen 1973). The high forest hypothesis proposes that prior to human disturbance, the primeval forests of lowland Europe were dominated by high, closed canopy, mixed deciduous trees. These forests would largely be dominated by Lime (*Tilia cordata*), elm (*Ulmus sp.*) and oak (*Quercus sp.*), with an understorey of hazel (*Corylus avellana*), ash (*Fraxinus excelsior*) and a range of shrubs (Birks 2005). The hypothesis assumes that much of the landscape is under mature forest, with regeneration taking place in gaps created by the death of an individual or group of trees (Bradshaw *et al.* 2003).

The high forest hypothesis has developed from the study of contemporary European forests (Peterken 1996). However these are often dominated by shade-tolerant species, including Beech (*Fagus*) which were not important or present in early-mid Holocene forests (Bradshaw *et al.* 2003). The theory has gained support by conventional, regional palaeoecological studies which generally lack a significant abundance of grasses or herbaceous species, indicative of open conditions, prior to the onset of agriculture (Bradshaw *et al.* 2003). Insect records also support this hypothesis, an abundance of insect remains associated with tree dependant species and a lack of species associated with large mammals such as dung beetles (Ponel 1995).

Potential problems with this hypothesis are that the large basin sites, such as peatlands and lake sites, used to support it have large pollen source areas which may lead to tree taxa being over-represented.

The wood-pasture hypothesis was compiled primarily by the work Vera in 2000. The hypothesis states that lowland woodland was covered by a mosaic of patches of woodland, scrub and savanna (Figure 2.1). The theory is derived from analysis of historical documents and modern ecological observations. Vera (2000) suggests that herbivore grazing pressure has been much more important in the past than traditionally believed and that this pressure would lead to the existence of these open areas. Bradshaw (2003) outlines the three major strengths of this hypothesis. Firstly that the areas of open land, woodland 'edge' habitats would allow for the generation of light-demanding species of oak (*Quercus*) and Hazel (*Corylus*) and other species which have difficulty in establishing under more closed canopies. Secondly, the shifting mosaic of open and wooded habitats would provide suitable conditions for a wide range of light demanding insects, herbs and bryophytes. Finally, the incorporation of large mammals into a more complete picture of forest ecosystems, a role that may well have been previously underestimated by many Holocene palaeobotanists (Bradshaw 2003).

Significant weak points of the hypothesis include a considerable lack of palaeoecological evidence to support the wood-pasture hypothesis (Bradshaw 2002; Bradhsaw *et al.* 2003; Mitchell 2005). The hypothesis also implies that there were large populations of herbivores including aurochs, bison and wild horse, however the palaeontological record does not support this (Bradshaw *et al.* 2003). Another weakness is the use of modern wood pasture systems which are all within managed systems containing large number of domestic animals (Bradshaw *et al.* 2003). Finally, Vera's (2000) views regarding the regeneration capabilities of oak (*Quercus*) have been challenged by Rackham (2003) and Peterken (2001) who suggest that the introduction of a fungal pathogen, oak mildew (*Microsphaera alpbitoides*) into Europe in AD 1907 has led to a reduced ability for oak (*Quercus*) to regenerate and compete, which probably did not occur in the past (Kelly 2002).

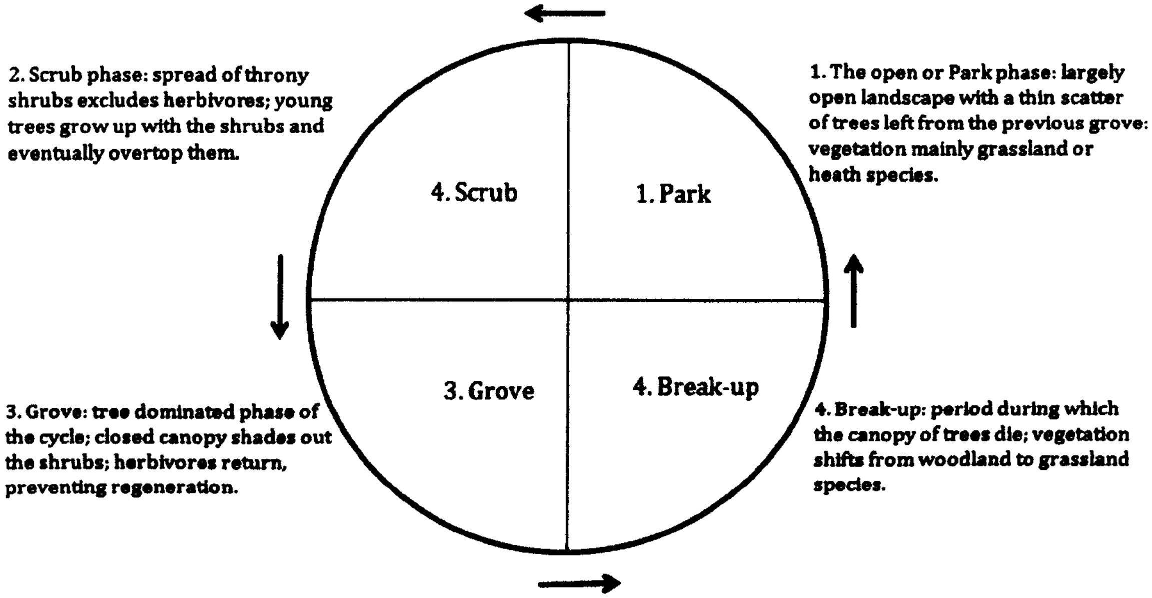


Figure 2.1: The wood-pasture hypothesis, consisting of three phases of open park, scrub and grove, to which a fourth has been added to represent the transition from woodland back to open habitat (Vera 2000).

Mitchell (2005) assembled modern pollen data from a variety of basin sizes from lowland Europe to test Vera's hypothesis of openness. Pollen data from small hollows showed that within closed canopy conditions at least 60% tree pollen is present. In open areas, tree pollen values of 50% or less were recorded. After calibration of modern tree pollen values in relation to the presence or absence of a closed canopy he applied this to fossil pollen assemblages from six small forest hollow assemblages (Sweden, Denmark and Ireland). Results of the calibrated fossil pollen assemblages indicated that closed canopy conditions were present throughout the early and mid-Holocene, with values dropping below 50% tree pollen during the past 3000 years. Mitchell (2005) concluded that there is no indication of open-forest canopies at a local scale at any of these sites prior to human impact, irrespective of the presence or absence of large herbivores.

Bradshaw *et al.* (2003) proposes a resolution that would involve a re-evaluation of former disturbance regimes in which browsing animals are represented more fully. The potential for a combination of both fire and browsing pressure may have created appropriate conditions for regeneration of oak (*Quercus*), hazel (*Corylus*) and pine (*Pinus*) without the development of a persistent or shifting mosaic of non-forest habitat (Bradshaw *et al.* 2003). However it is clear that further work is required to evaluate the merits of each hypothesis and assess their inadequacies, using present ecological studies wisely as analogues for past communities.

2.3 Naturalness, Conservation and the role of Palaeoecology

The term 'natural' can be defined in a variety of ways which can be both absolute and relative to what we are describing (Peterken 1996). The relevance of the term 'natural' in ecology and palaeoecology is important as different sectors consider 'naturalness' in differing senses, making it hard to communicate our findings to each other and successfully implement management.

'Natural' can mean vegetation which owes its features strictly to natural factors alone, and not to the activities of people (Peterken 1996). It is also possible to use this term to imply that these conditions have been present at all times in the past, 'virgin' vegetation. Peterken (1996) also refers to the use of 'natural' in the context of differing between urban and rural landscapes, meaning that even cultural rural landscapes are perceived as natural. Finally, the term 'natural' has also been used in an urban setting, defining an area such as a city park with planted borders, trees and sown lawn, it is 'natural' in contrast to the surrounding buildings and roads (Peterken 1996). In the rural context it is generally accepted that human actions past and present have had and continue to have an influence on vegetation, so 'natural' is viewed as 'naturally responsive' to both environmental and anthropogenic factors (Peterken 1996).

There is considerable discussion around the topic of humans being 'natural'. Should human activity within the landscape be viewed as a natural process within a larger ecological system? The concept of nature has undergone a series of changes: a creative force; a process of development; a specific state of the landscape that is rooted to primeval or original conditions. It would appear that even now personal views on this topic vary and perhaps this is where the problem of the concept of natural between disciplines can show itself. Peterken (1996 pp. 11) states that 'defining natural is not a matter of right or wrong, but of arriving at something useful for a particular purpose'. He goes on to say that his preferred view of natural is the wilderness definition, where it means 'in the absence of people', an absolute and clear concept from which an objective scientist can draw conclusions. The author's view is similar to that of Henry David Thoreau (Kehr 1983) 'mankind and nature form an ecological unity'. Perhaps this is due to the difficulty of using Peterken's (1996) concept on a palaeoecological timescale, as human activities have influenced European vegetation for at least 400 000 years (Bower 1997), though its potential for effect upon a large proportion of the landscape has only been realised in the past 6000 or so years. At what point do we define anthropogenic activity as ceasing to be 'natural'? The Darwinian view of human beings in the context of nature is similar to this; humankind has evolved alongside other species and will continue to do so (Darwin 1859, 1871, 1872). However this does not mean that our natural origins make our actions and outcomes of our actions natural, we do not have the right to over-exploit resources and damage ecosystems beyond repair.

It is also clear that our own personal perception of naturalness has implications on the conservation management of areas and ecosystems, after all if we have differing views of what natural is then we have differing views of what we are conserving or restoring. Siipi (2004) outlines the three modes of conservation and the implications of these methods and naturalness. Ecosystem preservation appears to be one of the most widely used methods of conservation, where human activity may be excluded completely from the site of conservation or changes in landuse are not permitted (Siipi 2004). Ecosystem restoration aims to make changes to the current state of a managed ecosystem or site, assisting the recovery of an ecosystem that has been damaged (Siipi 2004). Finally, ecosystem engineering, 'the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both' (Odum 2003).

Palaeoecology has an important role to play in the preservation and restoration of sites. It can provide information about the species that have been present at a particular site or within a particular ecosystem and for how long they have been present within the system. Palaeoecology can also provide us with a list of species which have been lost from a given site/ecosystem, therefore identifying those which should be reintroduced and those species which are considered not to be native to the area. It gives us an understanding of the vegetation dynamics that were in play prior to human activity and the degree of influence human activity has had on the system.

'Applied palaeoecology' is an emerging concept, that can address specific ecological and environmental questions, Birks (1996) notes that the developments in methodology and palaeoecological concepts can support this process. An example of palaeoecology informing conservation, restoration and management decisions can be seen from the results of a stand-scale palaeoecological investigation at Johnny's Wood, Lake District. This woodland is currently dominated by *Quercus* and *Betula* and is of high conservation importance due to its rich bryophyte flora and presumed naturalness (Ratcliffe 1977). The investigation revealed that the dominance of these taxa occurred in recent history, the past 500-700 years following likely anthropogenic disturbance (Birks 1996). As a result conservation efforts had been preserving a 'semi-natural' landscape which had formed as a result of disturbance. Lack of tree regeneration within this woodland was of particular concern to forest managers and palaeoecological investigation provided information regarding the potential change in landuse to aid restoration, (current high grazing pressure may have resulted in decreased tree regeneration) (Birks 1996).

To conclude, nature conservation is primarily concerned with the present and the future, however it is affected by past activities. Palaeoecology is concerned with the past and use the present as a key to interpreting the past (Birks 1996). Palaeoecology is a vital tool in conservation as it provides a prehistoric perspective.

2.4 Ancient woodland

Ancient woodland has been a debated topic in the British Isles for the past thirty years, mainly as a result of the work of Rackham (2003) and Peterken (1993). In the absence of palaeoecological data, there has been a tendency to view these 'ancient woodlands' as having some continuity with the original postglacial woodland cover (primary woodland) (Day 1993). It has also been suggested by ecologists working within this field, that certain plants which occur predominantly or solely in ancient woodland, are relict woodland species and that they are virtually incapable of colonising secondary woodland (Peterken 1974, 1981). However recent work has been conducted to investigate the true antiquity of these 'ancient woodlands' and the nature of the species which occupy them (Simmons 1964, 1965; Barkham 1978; Edwards 1986; Day 1993; Brown 2010).

Ancient woodland describes a site which has been continuously wooded since at least AD 1600 in England and Wales and AD 1750 in Scotland (Peterken 1977; 1996; 2008) or AD 1700 (Rackham 2003), i.e. woodland that originated prior to this threshold date. The use of these threshold dates relates to the onset of significant planting within the British Isles and also the period at which maps of woodland become more widely available. Therefore an assumption is made that an ancient woodland is a mediaeval or earlier wood which has likely never to have been planted. However ancient woodlands are not necessarily old-growth stands, they can and usually do have much younger trees and in some cases are entirely composed of young trees. It is the continuity of woodland at the site which determines its status as an ancient or recent woodland. Felling, coppicing, planting and other forestry operations do not interfere with the continuity, provided that woodland of some kind regenerates immediately afterwards (Peterken 1996). However if land-use is changed, then continuity is broken, for example opening of land for pasturage or cultivation.

Within this definition the use of 'primary' and 'secondary' woodland are used to distinguish between woodlands that have existed continuously since before the original forests in that district were fragmented, 'primary woodland', and those woods which have originated on un-wooded ground since that time and before AD 1600, 'secondary woodland' (Peterken 1996). All primary woodlands are ancient woodlands and all recent woodlands (those originating after AD 1600), are secondary. It is also possible to have an ancient secondary woodland, woodlands originating on un-wooded ground prior to AD 1600 (Peterken 1996). It is likely that a large proportion of ancient woodland sites are secondary woodland as palaeoecological evidence is now revealing that some of these sites were cleared in prehistory, for example the Killarney oakwoods, Ireland(Mitchell 1988, 1990).

Finally, there is a third classification of ancient woodland which is related to the species which are present. The woodland may be described as an 'ancient semi-natural woodland' (ASNW) or a 'planted ancient woodland site' (PAWS). These terms differentiate between woodland which is pre-dominantly composed of trees and shurbs that are native to the site and not obviously planted (ASNW) and planted woodlands of any species on ancient woodland sites (PAWS).

Field studies of supposed ancient woodland sites have relied upon 'ancient woodland indicators' (AWI's), a list of vascular plant species suggested to be confined to primary woodland or to occur as remnants of relatively undisturbed areas of former primary woodland (Peterken 1974, 1981; Rackham 2003; Peterken and Game 1984). However this list is not accurate for each site, there is regional variability (Day 1993). Ratcliffe (1968) also identified that desiccation-sensitive 'atlantic' bryophytes can be used as indicators, along with some lichens (Rose 1979).

To establish the true nature of an 'ancient' woodland palaeoecological investigation of long sedimentary sequences from within the woodland itself is required, however suitable deposits are rarely found (Day 1993). Scottish studies have largely been limited to pine woodland (Durno and McVean 1959; Birks 1970; O'Sullivan 1973). Edwards (1986) demonstrated that 'atlantic' bryophytes were present within four North Wales 'ancient woodlands', she demonstrated that despite some disturbance over recent centuries and episodes of clearance. Edwards (1986) also concluded that habitat availability is as important as woodland continuity in such sites. Irish sites include work done by Mitchell (1988, 1990) and Hannon and Bradshaw (1989). Mitchell (1988) conducted similar research to that of Edwards (1986) in two bryophyte-rich woodlands in the Killarney valley. Further studies in woodland on lake islands in Killarney and Connemara (Hannon and Bradshaw 1989; Mitchell 1990) revealed that woodlands once considered to be primary due to their isolation, were actually of recent origin or had undergone major disturbance.

There are limited long sequences from woodlands in lowland England. However there have been a series of studies within the New Forest (Barber 1975; Clarke and Barber 1987; Grant 2005), Epping Forest (Baker *et al.* 1978), Oxborough Wood, Norfolk (Bradshaw 1981b) and Sidlings Copse (Day 1993). Poor temporal resolution has hindered the certainty with which 'ancient' woodland status can be applied to these sites, however Oxborough wood is likely to be a secondary woodland due to cartographic evidence of nineteenth-century planting. Sidlings Copse (Day 1993) is likely to be a remnant of a large area of secondary mediaeval woodland, as a result of regeneration commencing approximately 1000 years ago.

Ancient woodland was identified as the most important category for nature conservation in 1981 by the Nature Conservancy Council (Thomas *et al.* 1997), a government body concerned with nature conservation no longer in existence today. This resulted in the creation of a ten year long project to identify and list ancient woodland sites, the Ancient Woodland Inventory (AWI) (Spencer and Kirkby 1992). The AWI established that there was a total of 340 66 ha of ancient woodland in England (Spencer and Kirkby 1992). Ancient woodland is still of significant conservation status and efforts are underway to restore and re-plant on ancient woodland sites in an effort to increase the area of ancient woodland and maintain species biodiversity (UK Biodiversity Action Plan 2010; Native Woodland Habitat Action Plan 2007).

2.5 Pollen Analysis

Pollen analysis is a method that has been used since the turn of the twentieth century (Faegri, Iversen, Krzywinski 1989), to investigate past pollen assemblages from past environments. A pollen assemblage includes pollen grains produced by seed plants, angiosperms and gymnosperms; and spores produced by pteridophytes, bryophytes, algae and fungi. If pollen from a stratified sequence is used, it is possible to investigate the changing types and amounts of pollen arriving at the site of deposition over time. Exact time-scales of pollen deposition can be supported by collecting radiocarbon dates from the sediment. These data can then be used to explore and interpret changes in vegetation history, climate and human activity. Additional methods can be used to support pollen analytical findings, such as plant macrofossils and charcoal. These can be used to investigate local vegetation over a given time period and vegetation dynamics influencing vegetation structure and composition, such as charcoal. There are a variety of depositional environments where pollen can be found and studied, these include deposits from lakes, peat bogs, buried soil.

However as with any method, there are inherent problems with pollen analysis, including degradation of the stratigraphy of sediment by biological activity, movement of humic material potentially resulting in a down-washing of pollen from more recent sediment. Preservation of pollen grains themselves also differs from site to site, these too can be as a result of biological activity or changes in depositional environment, such as drying of the sediment.

The differing environments in which pollen is deposited and preserved can lead to difficulty in the interpretation of the pollen assemblage, as a result studies have been conducted to investigate transportation and deposition of pollen at depositional sites. It is also essential to understand the methods of pollen dispersal and the characteristics of the depositional environment.

2.5.1 Pollen dispersal, transport and deposition

For pollen to be deposited in sediments it must first be released by the plant. Pollen is produced by the anther of the flower and is dispersed in a number of ways, notably high- and low-level air borne transport and via water-borne pathways in runoff and streams (Tauber 1965) in an effort to reproduce. Pollen which is dispersed by wind is most common in northwest European plants, especially common tree types and are referred to as anemophilous taxa; they are well represented in the pollen record. The extent of dispersal of anemophilous species pollen is dependent upon the size of the pollen grain, i.e. the smaller the grain, the greater potential it has to travel. Although wind-borne dispersal mechanisms are most common, pollen grains can also be dispersed by vertebrates (zoophilous plants) for example *Galium,* pollen grains from these plants are generally too heavy for wind-dispersal; Insect pollinated plants (entomophilious plants), pollen grains of these species are generally larger than those mainly dispersed by the wind; there are also a variety of self-fertilising plants (autogamous); either by not flowering (cleistogamy) for example many species of Poaceae and *Fabaceae*; Monoecious species have unisexual male and female organs on the same plant. Pollen is also produced by aquatic species which can release their pollen underwater, these are called Hyphyrogamous species and their representation in terrestrial pollen records is poor.

The method of transport of pollen within a forest environment was investigated by the Danish palynologist, Henrik Tauber (1965, 1967 &1977). Tauber (1965, 1977) suggested that pollen is transported largely by five pathways (components) to the site of deposition (Figure 2.2): streams and surface runoff (Cw), through the trunk space (Ct), above the canopy (Cc), by rainfall (Cr) and by gravity (Cg). Tauber (1965, 1967) also predicted that these components would be represented in different proportions depending upon the size of the basin of deposition, for example a smaller basin would have more trunk space (Ct) derived pollen than a large basin. However Tauber (1965, 1965) did not acknowledge the importance of Cw and Cg on smaller sites (Jacobson and Bradshaw 1981).

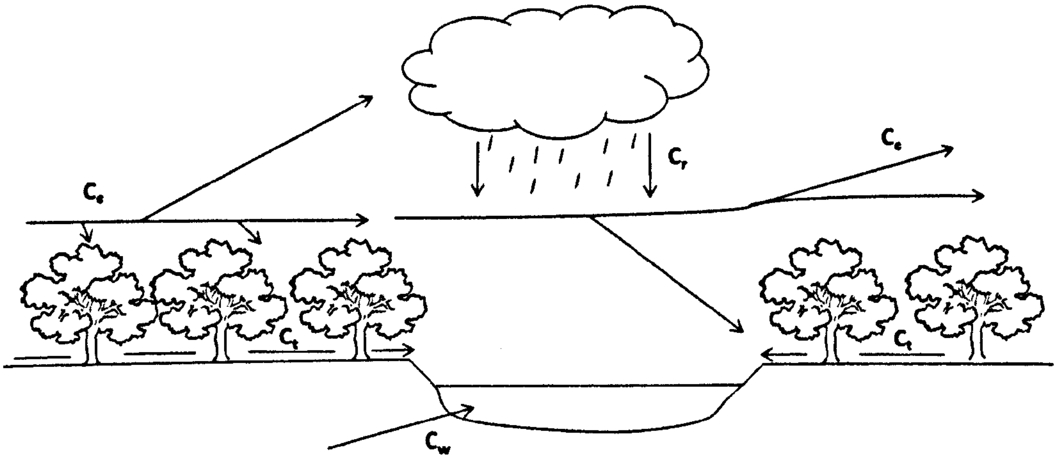


Figure 2.2: Diagram showing the varying methods of pollen transportation to a small mire or lake (adapted from Moore *et al.* 1991).

After work done by Janssen (1966) modelling the relationship between the magnitude of pollen deposition at a site and the areas from which the pollen grains originated, either local, extra-local, regional or extra-regional, Jacobson and Bradshaw (1981) suggested a relationship between basin size and pollen source area, providing there are no inflowing streams (Figure 2.3). However there are two factors that may affect the relationship between source area and basin, firstly, if the canopy above the basin opened it is likely that more extra-local and regional pollen would be deposited at the basin. Secondly, if the runoff and stream (Cw) component were to be involved, then pollen source area would increase (Parsons *et al.* 1980).

Within closed forests Andersen (1970) and Bradshaw (1981) showed that most pollen does not travel more that 20-30m from the source area, although some pollen grains may originate from greater distances, it is likely that these will be swamped by pollen from local vegetation (Jacobson and Bradshaw 1981). This assumption cannot be applied to all pollen types, as for example, pollen from *Pinus* and *Quercus* in a lake will have originated from a source area far larger than that of *Fagus* (Bradshaw and Webb 1985). Therefore pollen source area is dependent on both the size and type of the site and on the pollen types under consideration (Jacobson and Bradshaw 1981).

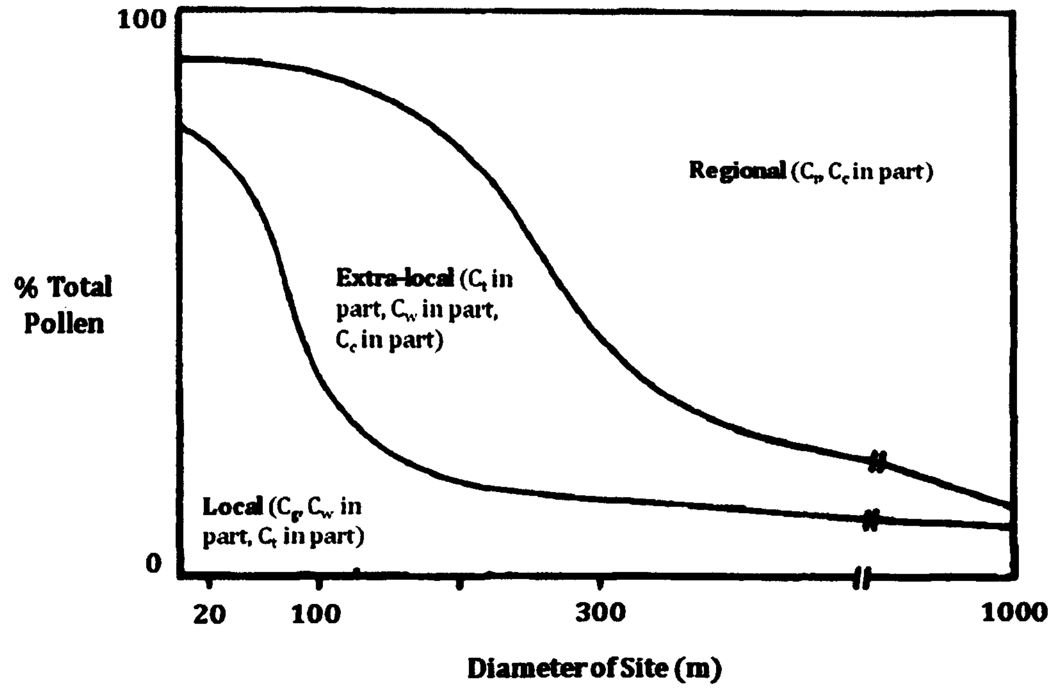


Figure 2.3: The relationship between size of the deposition site and the various sources of pollen entering it (re-drawn from Jacobson and Bradshaw 1981).

These earlier models of pollen representation have now been considerably refined by Sugita (1993, 1994, 2007a, 2007b) and work within the POLLANDCAL network. The approach developed by the group relies upon developing modern pollen/landcover relationships from a range of geographic locations to develop and test mechanistic model-based approaches to quantification of vegetation cover from pollen data. Sugita (2007a, 2007b) has developed the REVEALS model that estimates regional vegetation compositions using pollen from large lakes which have small site-to-site variations in pollen assemblages. These data can then be used to quantify the regional vegetation composition, which can then be used to estimate conditions at smaller sites to effectively reconstruct vegetation in smaller areas (Sugita 2007a, 2007b). Further developments made by Sugita (2007b) resulted in creation of the LOVE (Local Vegetation Estimates) model. The LOVE model estimates the local vegetation composition within the relevant source area of pollen, by quantifying and then subtracting the background pollen to create a quantitative reconstruction of local vegetation (Sugita 2007b).

2.5.2 Pollen Preservation

This is an important consideration when attempting to interpret a pollen sequence. Some experimental work was done by Cushing (1967) showing that different species of pollen are susceptible at differing levels to degradation and corrosion. Susceptibility to corrosion also have links with the type of deposit, for example a highly minerogenic deposit will be more susceptible than a highly organic deposit such as peat. The ability for the palynologist to identify pollen species is hindered by the degree of the degradation and the species which are being identified, for example, the *Tilia* pollen grain has three distinctive pores and so can be identified relatively easier than a *Quercus* grain that has been subjected to the same corrosion.

Five classes of preservation have been suggested by Cushing (1967):

- Corroded: grains whose exines are affected by a distinctive etching or pitting.
- Degraded: grains whose exines appear to have undergone a structural rearrangement, so that sculptural and structural details are resolved only with difficulty.
- Crumpled: grains that are badly folded, wrinkled, or collapsed.
- Broken: grains whose exine is ruptured.
- Well-preserved: intact grains with no or little signs of the above types of preservation.
- Obscured grains: not mentioned by Cushing (1967), but another factor that affects the identification of pollen, this is usually as a result of preparation techniques, for example acetolysis.

2.5.3 Pollen Interpretation

Interpretation of pollen diagrams is dependent upon a variety of aspects, including the techniques employed and the experience of the analyst. Direct comparisons can be made between past pollen assemblages and recent pollen assemblages obtained from surface sampling, however this can only be successful when modern vegetation is a true analogue of the past vegetation. However the nature of the sample site determines the potential for this type of comparison. In natural areas this methodology is more useful than in cultivated areas, where the vegetation structure is no longer similar to that of the structure that the fossil pollen assemblage represents.

When interpreting the pollen diagram it is also important to understand the spatial patterns in vegetation, as variations in pattern are likely to affect the source components within the sediment, i.e. local, extra-local, regional and extra-regional. Therefore, to enable a meaningful direct comparison between recent assemblages and fossil assemblages, the specific spatial pattern of vegetation must also be mimicked (Sugita, 1993, 1994, 2007a, 2007b, Grant 2005)

Pollen sequence interpretation also relies upon an understanding of individual and community characteristics (Grant 2005). Janssen (1981) identified two main approaches to ecological interpretation of a pollen sequence:

- Autecology-synecology relationships: This approach is based upon an understanding that there are variations in pollen dispersal techniques between taxa this will lead to differences in representation at the depositional site. These variations will result in certain taxa having a more local abundance and therefore lower representation in the pollen sequence, as opposed to well dispersed pollen taxa that produce large quantities of pollen from a larger source area, therefore representing a larger range of plant communities (Grant 2005).
- Synecology-stratigraphic relationships: This approach is based upon the use of pollen types as an indicator of vegetation types, due to individual plant species not occurring everywhere within their distributional area, but restricted to specific vegetation types (Grant 2005). In this case the interpretation of the fossil pollen diagram relies upon the grouping of pollen types into pre-determined ecological groups based upon their modern ecological context.

2.6 Charcoal Analysis

Patterson (1987) describes charcoal as 'an amorphous inorganic carbon compound which results from the incomplete combustion of plant tissues'. Charcoal is generally well preserved in the palaeoecological record and can therefore be used to reconstruct past fires. Preserved fragments of charcoal are normally classified in terms of their size, as micro- or macro-charcoal, however the actual particle size that differentiates between these classes is dependent upon the analyst and the method employed. In general microscopic charcoal is that requiring a high-powered microscope to view, generally less than 100μm and often recorded alongside pollen analysis. Macro-charcoal particles are usually greater than 100µm and can be divided into other size classes depending upon the method used (for example, the size of sieve mesh(es) used), they are usually viewed using a low-powered stereomicroscope.

Charcoal analysis can provide information about human activity in the area, allowing for more detailed interpretation of the pollen record, it can also provide data to investigate the natural fire regimes.

2.6.1 Burning in British woodlands

Rackham (2003) states that a majority of British woodland is very difficult to burn, even under drought conditions, and that natural fires are rare, mainly relying on the presence of *Pinus sylvestris*. Peterken (1993) also agrees that the broad-leaved deciduous woodlands of the British Isles are lacking in susceptibility to burn. The use of fire in the British uplands during the Mesolithic has become a common view, supported by Simmons (1969, 1975, 1996) and Innes and Simmons (1988). Moore (2000) suggests that there has been a belief that human manipulation of forests through firing first took place in the uplands during the Mesolithic, however lowland fires of natural or anthropogenic ignition did not occur. However past investigations have provided evidence that it is not only *Pinus sylvestris* that burns in British woodlands. Whitehouse (2005) recorded the presence of burnt roots, stumps and trunks of both *Pinus sylvestris* and *Betula* from Thorne Moors, dated between 5300-4300 cal. years BP. The material from Thorne Moors (Whitehouse 2005) was attributed to natural fire in a *Pinus sylvestris* mire. Fauna attributed to burning within woodlands has also been found (Buckland 2005), with the presence of pyrophilic beetle assemblages from sites dating to the mid-Holocene, suggesting that natural burning occurred in past woodland.

2.6.2 Human use of fire

Moore (2000) noted that although the general consensus is that the woodlands of lowland Britain were not susceptible to burning, given the right set of circumstances and a knowledge of the environmental factors favourable for burning, it would be possible to burn. The difficulty to disentangle natural versus human activity; and whether charcoal is actually as a result of burning of vegetation, can make it difficult to truly understand these questions (Grant 2005). There are a variety of methods that can be employed by humans which can result in the production of charcoal, these have been clearly stated by Grant (2005), Table 2.1. The use of fire by humans is also related with the site at which the burning is occurring (occupation period and size of group), the environmental (Climate, types of energy supplies) and human (energy needs, fuels selection) determinisms and the method of burning employed (production, cooking, size of fire). The most important variables include fuel availability (Théry-Parisot 2002).

Table 2.1: Potential anthropogenic activities that may produce charcoal within the a sedimentary sequence, (Grant 2005).

Method	*Effect*
Slash and Burn (swidden) techniques	System associated with a frequent settlement mobility whereby burning is used to aid clearance of areas of woodland for early crop production. Associated with Landnam activity.
Managed Woodland	Burning may be used to dispose of unwanted plant material, such as twigs and leaves after coppicing/pollarding. Burning would also have been used for fires in small 'base camps' during these operations.
Charcoal burning and Production	Wood harvested from managed woodland may be converted to charcoal as it burns at a higher temperature, is easier to light and lighter to carry.
Heathland Management	To preserve an open environment, burning is frequently used to destroy gorse and tree-sapling growth, and may have a preferential affect upon heather growth.
Arson/Accidental Cause	Purposeful, or accidental burning, for example, unattended campfire, or the discarding of glass or naked flames.
Settlements	Burning of wood or charcoal for cooking, warming, or other domestic purposes.
Industry	For example, Pottery production or Metallurgy.
Invasions/Battles	Burning of settlements during an invasion, or a battle encampment in the near vicinity would create a cluster of fires to feed troops and produce warmth overnight.

2.6.3 Methods

Charcoal is produced between temperatures of 280°C and 500°C (Chandler *et al.* 1983). High temperatures result in the conversion of material to ash through glowing combustion and lower temperatures can lightly score material (Whitlock and Larsen 2001). Charcoal fragments are identified by their opaque, angular, usually planar, black fragments. However when looking at samples it is possible to identify other black fragments that broadly fit these criteria, such as minerals, plant fragments and insect cuticles. There are a variety of techniques that can be used to differentiate between these fragments, mineral material can be differentiated by their crystalline form (Clark 1984). Plant material can be distinguished by applying pressure using a dissecting needle; charcoal fragments fracture under pressure where as plant material will impale or compress. It is also possible to use certain methodological procedures to aid differentiation between dark plant material and charcoal fragments, for example bleaching of sediment resulting in a lightening of non-charred material. Insect cuticles are generally thinner than charcoal fragments.

A significant issue in fire-history studies is the lack of a standardised methodology for preparation of samples for analysis, quantification and presentation. This has resulted in a variety of techniques being used and a lack in ability to compare records easily. Fire occurrence methods generally focus of microscopic charcoal (<100μm) on pollen slides (Swain 1973; Cwynar 1978; Clark 1982). This method usually results in the number or area of charcoal particles being calculated as a result of counting along a series of traverses on the pollen slide or on a grid. These data are presented as charcoal accumulation rates, percentage of pollen sum, or as a ratio of the pollen sum. It is widely accepted that this material is indicative of regional fires, as small particles can travel great distances (Clark 1988a; Odgaard 1992). Macrocharcoal is believed to represent a more local source area (Clark 1988a). Again, data are presented as accumulation rates of area or particle number, fire frequency can also be calculated when continuous samples have been analysed (Whitlock and Larsen 2001). There are inherent problems with each of these methods (see table 2.2), as a result other methodologies have been explored, including chemical digestion to calculate charcoal abundance by weight (Winkler 1985; Laird and Campbell 2000). The chemical digestion methodology removes the need for size classes and subjective analysis, however problems encountered include inaccuracy in measurement as a result of inability to measure small quantities of charcoal and weight-losses associated with decomposition of clay materials upon ignition (MacDonald *et al.* 1991).

2.6.4 *Microscopic charcoal*

The use of pollen-slide charcoal as a fire proxy was first recognised by Iversen (1941) and today, the method is widely used. Samples for microscopic charcoal analysis are prepared as part of routine pollen preparations. Clark (1984) identified that differences in pollen procedures should be kept to a minimum as this affects the charcoal area on pollen slides. Charcoal area can be calculated from size classes, point-counts or computerised imaging techniques (Table 2.2) (Whitlock and Larsen 2001). The size-class method involves the measuring of the area of each particle using a gridded eyepiece in the microscope (Waddington 1969), recording the size of each piece ore placing each particle into a size class. Geometric size classes are usually used as large particles are generally not present. Clark (1982) introduced the 'point-count' method which involves selecting random points on the pollen slide and determining percentage points that overlie charcoal.

2.6.5 Macroscopic charcoal

There are two main methodologies employed in the preparation and analysis of macrocharcoal; the thin-section method and the sieving method. The thin-section method is mostly used with varved sediments as it permits fire history reconstructions with annual precision (Clark 1988b). It has also been used on other sediments apart from lakes, Anderson and Smith (1997) used this method on eight wet-meadow cores in the Sierra Nevada, California. The sieving method is considerably cheaper than the thin-section method and relatively quick (Table 2.2). Samples used for this method are generally sampled continuously throughout the core, usually 1cm thick. Between 1 to 5cm^3 of wet sediment is used per 1cm slice. Each sample is soaked in a deflocculant for a 24-72 hours and then gently washed through a series of nested sieves, ranging from 125μm to 500μm meshes. The resulting data is then converted to charcoal concentration and can be converted to charcoal accumulation rates.

In recent years additional processes have been added to the sieve method, including the use of image analysis software which allow for a semi-objective method of analysing the charcoal area of a sample as a result of optical density (Mooney and Radford 2001; Mooney and Black 2003).

2.6.6 Presentation of results

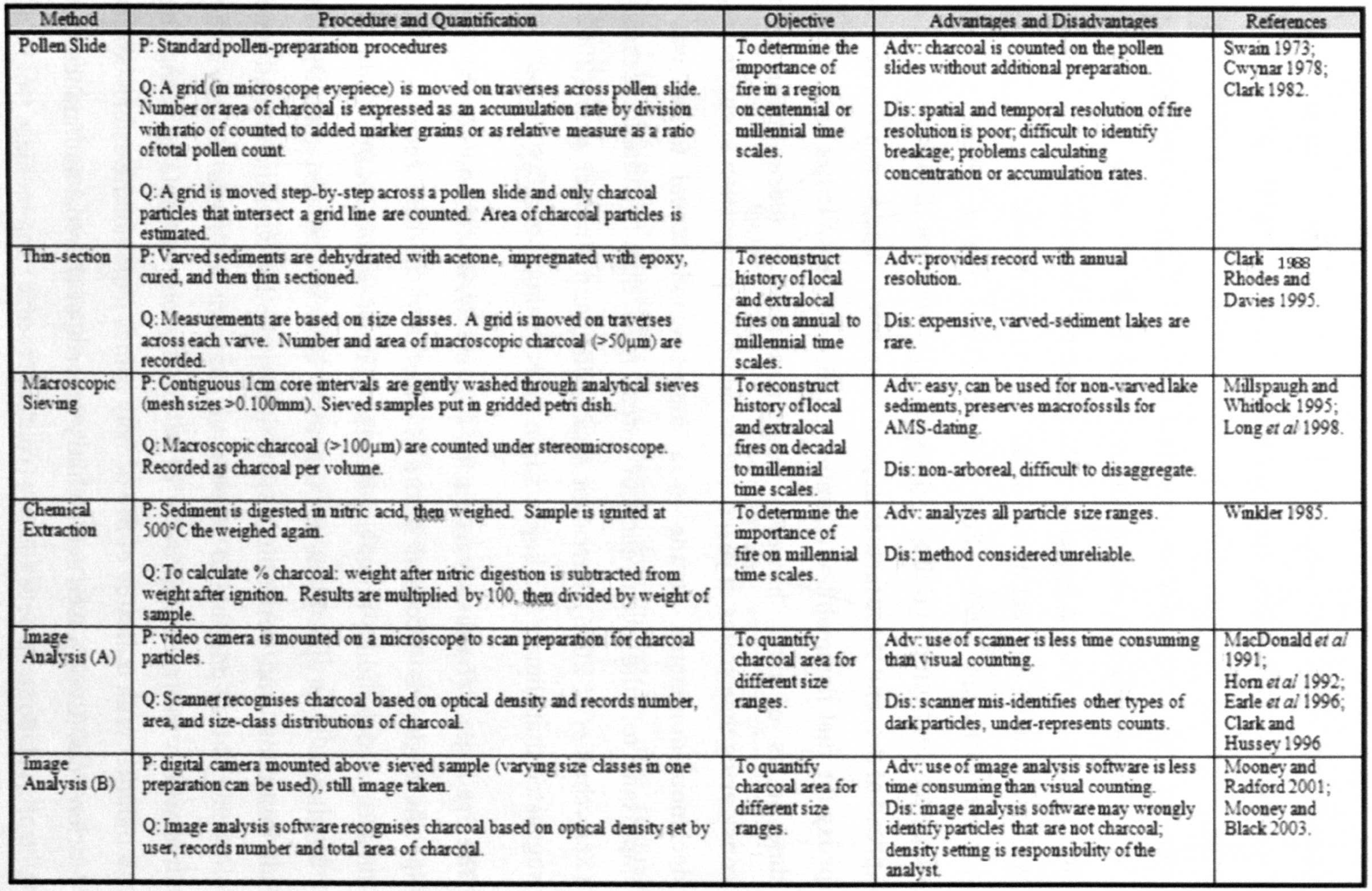
Charcoal data can be presented in a number of ways: volume or area of particles in specified size classes; total volume or area of charcoal; pollen-charcoal ratio;

number of particles identified; and finally abundance estimate (on a scale). The latter of these examples has potential problems and is difficult to compare within the core and between sites, as accumulation rates may have varied throughout the core, therefore affecting concentrations.

Particles encountered is a quick, quantitative method, however problems can include a false peak in charcoal fragments caused by the fractionation of particles during preservation or preparation. The pollen:charcoal ratio is a useful quantitative method, however care must be taken when the presence of pollen from taxa of heavy pollen producers are present as this will alter the ratio.

To overcome such problems as fractionation as a result of processing, the area or volume method appears to succeed, as fractionation of particles does not significantly affect the overall volume (Grant 2005). These results scan be represented as absolute volume or area per volume. Finally, splitting charcoal fragments into size classes allows for some interpretation regarding the nature and the source area of the charcoal and therefore locality of the fire event. However care must be taken when using this method, to note the amount of processing involved prior to analysis, as fractionation can occur during preparation resulting in a greater number of smaller particles. In general smaller size classes are associated with burning events at a considerable distance to the site, whereas large size classes are associated with local burning.

Table 2.2: Methods of charcoal analysis (adapted from Whitlock and Larsen 2001).



Method	Procedure and Quantification	Objective	Advantages and Disadvantages	References
Pollen Slide	P: Standard pollen-preparation procedures Q: A grid (in microscope eyepiece) is moved on traverses across pollen slide. Number or area of charcoal is expressed as an accumulation rate by division with ratio of counted to added marker grains or as relative measure as a ratio of total pollen count. Q: A grid is moved step-by-step across a pollen slide and only charcoal particles that intersect a grid line are counted. Area of charcoal particles is estimated.	To determine the importance of fire in a region on centennial or millennial time scales.	Adv: charcoal is counted on the pollen slides without additional preparation. Dis: spatial and temporal resolution of fire resolution is poor; difficult to identify breakage; problems calculating concentration or accumulation rates.	Swain 1973; Cwynar 1978; Clark 1982.
Thin-section	P: Varved sediments are dehydrated with acetone, impregnated with epoxy, cured, and then thin sectioned. Q: Measurements are based on size classes. A grid is moved on traverses across each varve. Number and area of macroscopic charcoal (>50μm) are recorded.	To reconstruct history of local and extralocal fires on annual to millennial time scales.	Adv: provides record with annual resolution. Dis: expensive, varved-sediment lakes are rare.	Clark 1988 Rhodes and Davies 1995.
Macroscopic Sieving	P: Contiguous 1cm core intervals are gently washed through analytical sieves (mesh sizes >0.100mm). Sieved samples put in gridded petri dish. Q: Macroscopic charcoal (>100μm) are counted under stereomicroscope. Recorded as charcoal per volume.	To reconstruct history of local and extralocal fires on decadal to millennial time scales.	Adv: easy, can be used for non-varved lake sediments, preserves macrofossils for AMS-dating. Dis: non-arboreal, difficult to disaggregate.	Millspaugh and Whitlock 1995; Long *et al* 1998.
Chemical Extraction	P: Sediment is digested in nitric acid, then weighed. Sample is ignited at 500°C the weighed again. Q: To calculate % charcoal: weight after nitric digestion is subtracted from weight after ignition. Results are multiplied by 100, then divided by weight of sample.	To determine the importance of fire on millennial time scales.	Adv: analyzes all particle size ranges. Dis: method considered unreliable.	Winkler 1985.
Image Analysis (A)	P: video camera is mounted on a microscope to scan preparation for charcoal particles. Q: Scanner recognises charcoal based on optical density and records number, area, and size-class distributions of charcoal.	To quantify charcoal area for different size ranges.	Adv: use of scanner is less time consuming than visual counting. Dis: scanner mis-identifies other types of dark particles, under-represents counts.	MacDonald *et al* 1991; Horn *et al* 1992; Earle *et al* 1996; Clark and Hussey 1996
Image Analysis (B)	P: digital camera mounted above sieved sample (varying size classes in one preparation can be used), still image taken. Q: Image analysis software recognises charcoal based on optical density set by user, records number and total area of charcoal.	To quantify charcoal area for different size ranges.	Adv: use of image analysis software is less time consuming than visual counting. Dis: image analysis software may wrongly identify particles that are not charcoal; density setting is responsibility of the analyst.	Mooney and Radford 2001; Mooney and Black 2003.

2.6.7 Fire regimes

Fire regime is a term used to encompass the patterns of fire frequency (occurrence defined by number of ignitions), fire sizes (this is reliant upon landscape patterns, topography and rates of spread), and fire effects for a given area and over a defined time (Johnson 1992). Johnson (1992) states that weather and climate play an important role in fire ignition and spread (Figure 2.4). Fuel moisture is also an important factor in the ability for a fire to take hold, this is controlled by temperature and precipitation (Littell *et al.*. 2009), with wind being a direct driver of the rate of fire spread (Viegas 1998, Keeley and Fotheringham 2001). Fuel moisture (Viegas *et al.* 1992), fuel load, and diameter distribution (Hall and Burke 2006) influence the ignition and rate of spread of fire, and these factors depend upon forest type, which can be used as a proxy for fuel flammability (Cumming 2001). These factors are important in time scales of days, however vegetation type is more important when considering time scales of years. For example the proportion of coniferous- and deciduous-dominated stands in a mixed wood boreal forest was more important for the occurrence of forest fires than weather characteristics (Krawchuk *et al.*. 2006). Carcaillet *et al.* (2001) and Whitlock *et al.*. (2003) have suggested that climate is a key factor in determining forest fire characteristics.

The fire regime (frequency, intensity, seasonality, extent and type of fire), in a specific region is recorded in the sedimentary charcoal records to varying timescales depending upon the deposit (Power *et al.* 2008). Total charcoal abundance is proportional to the total biomass burned and depositional environments and depending upon depositional environment and sampling procedures it is possible to resolve the charcoal record to identify individual fires within the record (Power *et al.* 2008). An example of using charcoal abundance as an indicator of fire activity comes from northwestern USA, where Marlon *et al.* (2006) used sedimentary records of charcoal abundance to reveal a strong relationship between fire (charcoal record) and biomass (fuel load).

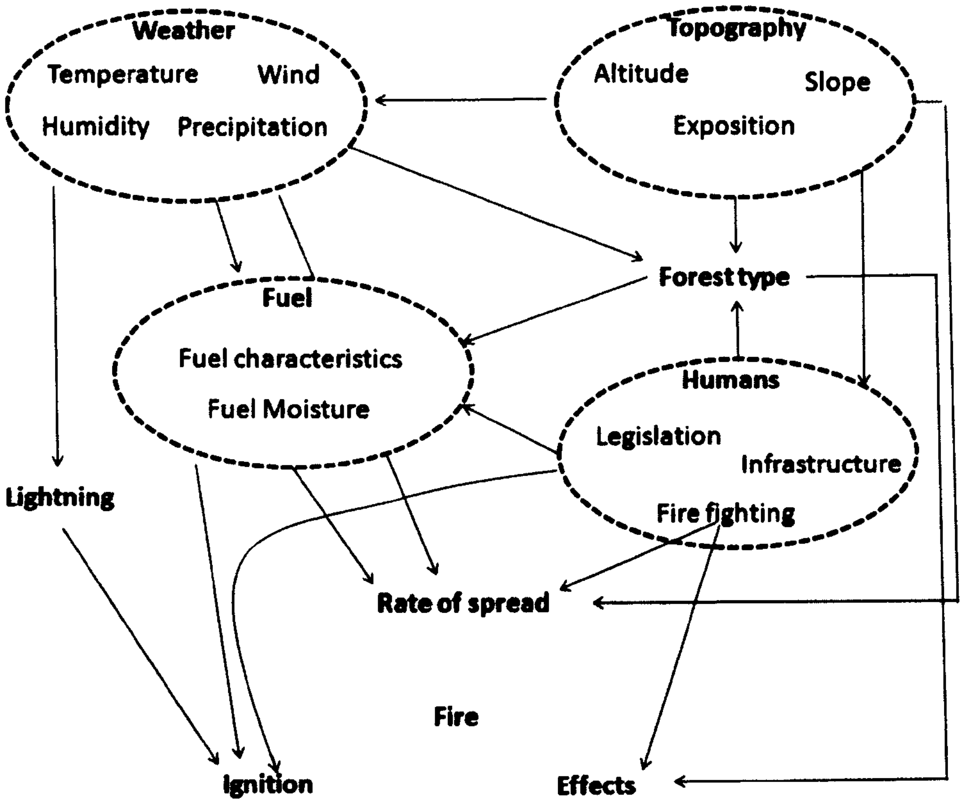


Figure 2.4: Conceptual framework of factors influencing the fire regimes (Weibel 2009).

2.6.8 *Charcoal databases*

As discussed previously, charcoal analysis as a proxy for fire has been used since the 1940's (Iversen 1941),however the variety of methodologies used has resulted in inherent problems in comparing data from different sites and authors/analysts. There has however been some success. The Global Palaeofire Working Group (GPWG) has been in existence for over four years and over this time they have compiled over 450 charcoal records from around the globe (Power *et al.* 2008). The main aims of the GPWG are to continue to compile the Global Palaeofire Database and use this database to assess fire activity over given periods of time, for example since the last glacial maximum (Power *et al.* 2008). The database is also publically accessible and as a result other researchers are able to use the database to aid their own research.

The European Charcoal Database was created as a result of the FIREMAN project, a BIODIVERSA funded project. The project aims to establish fire-biodiversity baselines for boreal forest, wet upland heathland/moorland and Mediterranean shrub-forest systems; create a continental scale model of climate-fire-vegetation relationships which will then inform national and European policy and model future scenarios. The British Isles Charcoal Database which was created as a result from work for this thesis has been incorporated into the European Charcoal Database and has been partially included in the Global Charcoal Database.

2.7 Dating and Chronology

Dating of sediments is integral to this thesis, whether it be the dating and age-depth modelling of sediments collected by the author or the inclusion of dated profiles in the charcoal database (see Chapter 5). There are a variety of dating methods that can be used when determining the chronology of a sedimentary profile, these include: Radiometric methods such as Radiocarbon, Lead ^{210}, Luminescence, Uranium-Thorium; Incremental methods including Varve chronology and Dendrochronology; and Age equivalent horizons (Isochrons) for example Palaeomagnetism and Tephrachronology. However the following review will concentrate on the use of radiocarbon dating, as this was the primary technique used within the thesis.

Radiometric dating methods have been used since the second half of the twentieth century. The principle involves the radioactive properties of materials which contain a natural time signal, most often isotopic decay (Roberts 1998). Radiocarbon dating was pioneered by Willard Libby in the late 1940's (Burleigh 1981). Radiocarbon dating involves the decay of Carbon -14 (^{14}C), which occurs at a stable rate. ^{14}C is present within all living organisms and when they die ^{14}C is not replenished and the isotopic clock is started.

The results of radiocarbon dating are normally presented as years before present (yrs BP), in practice the present is taken to be AD 1950. Radiocarbon dates are generally calibrated using programs such as CALIB or OxCal (Ramsay

1995), to remove any discrepancies between radiometric and historical chronologies. There are also a variety of potential sources of contamination, i.e. introduction of carbon either older or younger into a sample to be dated, these can include penetrating rootlets and the migration of mobile organic components (e.g. fulvic acid). Improvements in the radiocarbon dating method include the development of Accelerator Mass Spectrometer (AMS) dating method that allows the dating of smaller samples, resulting in investigators ability to select specific material such as seed remains or charcoal fragments (Roberts 1998).

Specific issues relating to the radiocarbon dating of both peat and mor humus will now be discussed, as these were the only materials collected during this investigation.

Radiocarbon dating of peat profiles is relatively common. The use of this material, however, is not without issue. In recent years there has been discussion as to the method of preparation and therefore the fraction of sediment that is dated. There appear to be slight discrepancies between the humic acid, humin and fulvic acid fractions (Shore *et al.*1995). Shore *et al.* (1995) investigated these discrepancies using neighbouring short-columns of peat and altering preparation methods to date these three fractions. The conclusions of these experiments included the relatively consistent younger age of the fulvic acid component compared to both the humic acid and humin component. However the variation between humic acid and humic components was not consistent with each being either older or younger relative to the other fraction at that level (Shore *et al.* 1995). In this thesis, the humin component was analysed for each site, which is the less mobile component of the peat profile (Shore *et al.* 1995).

Mor humus is a dry, acidic accumulation of partially decomposed plant litter of very low biological activity (Bradshaw 2007). Radiocarbon dating of mor humus material can be difficult due to the mobility of soluble organic acids as the continuing passage of humic acid may rejuvenate the ^{14}C activity of humus in lower horizons (Scharpenseel 1971). However previous studies have been successful; Scotland (O'Sullivan 1973), Northern Ireland (Cruickshank and Cruickshank 1981) and Denmark (Iversen 1969), there appear not to have been any published studies in recent years.

2.8 Stand-scale palynology

As previously discussed, there are a variety of depositional environments and spatial scales at which palynology and charcoal analysis can be investigated, however this thesis is primarily concerned with the use of palynology to investigate stand-scale changes in vegetation composition. Stand-scale palynology is the study of pollen preserved close to its source vegetation, generally in sediments accumulated within the woodland and under the forest canopy (Bradshaw 2007). Stand-scale investigations not only have applications in quaternary science, but also provide useful data for management and conservation of a site as detailed long-term ecological information is provided. Conventional pollen analysis provides data at large temporal and spatial scales, which are unfamiliar to those involved in contemporary ecology.

Stand-scale studies first began in Scandinavia and their potential to provide insights into dynamic ecological processes were first realised by Iversen (1964) in the Draved Forest, Denmark, where in 1949 he had established a field laboratory of 200ha. Iversen investigated pollen-vegetation relationships, monitored vegetation and conducted pollen analysis from 30 stand-scale sites within the forest.

Andersen (1970) investigated pollen representation at the stand-scale and developed correction factors to relate pollen counts and source vegetation more closely. During these studies, Andersen found that pollen grains appeared to land closer to source vegetation than was predicted by physical laws describing the dispersal of small particles, attributing this to turbulent air movement under the forest canopy. He showed that pollen sampled at one point on the forest floor has largely originated from vegetation within 20-30 metres of the sample site (Andersen 1970). These findings were later development by Prentice (1985), accounting for the specific properties of such sites and his approach provided the foundations for later pollen production and dispersal models. Further developments in the subject were made by Bradshaw (1981a; 1988), Sugita (1994), Mitchell (1998).

2.8.1 Depositional sites

Stand-scale palynological investigations can be investigated using sediments from a variety of settings beneath the forest canopy (Figure 2.5). However if the forest canopy is temporarily or permanently removed, pollen contained within these sediments will be composed of an increased proportion from vegetation far from the stand-scale vegetation which was represented under closed-canopy conditions (Table 2.3) (Bradshaw 2007). Suitable samples site have been surmised by Bradshaw (2007): accumulations of mor humus; soils of low biological activity; and small forest hollows.

Table 2.3: Properties of depositional sites used for stand-scale palynological analysis, (adapted from Bradshaw (2007).

	Small Forest Hollows	***mor humus***	***Soils***
Length of record (years)	Thousands	Hundreds to Thousands	Decades
Continuity of record	May be patchy	Good	Poor
Temporal resolution (years/sample)	10-100	1-10	n/a
Mixing or downwash of pollen	Minimal	Minimal	Yes
Pollen preservation	Usually good	Good	Poor
Macrofossils	Occasionally present	No	No
Charcoal	Present	Usually present	Usually present
Site availability	Restricted	Restricted	Widespread

Small Forest Hollows (Figure 2.5) are small topographical depressions in the forest floor, in which sediment accumulates. The sediment within these depressions may be mud or peat, and pollen within the sediment is usually preserved by waterlogging (Table 2.3) (Bradshaw 2007). Sedimentation can be either continuous or discontinuous, depending upon the potential for fluctuation in the local water table. Discontinuous sedimentation can be identified by abrupt changes in sediment composition and/or pollen composition and preservation (Jacobson and Bradshaw 1981). It is also possible to find plant macrofossils within such sediments (Hannon *et al.*. 2000).

Figure 2.5: Small Forest Hollow with wet sediment accumulation in the centre of the picture, Southern Germany (taken by C. Jones 2006).

Mor humus is a dry, acidic accumulation of partially decomposed plant litter of very low biological activity (Bradshaw 2007). Handley (1954) considered the formation of mor humus to be a function of chemical properties of the litter of certain plants, concluding that the presence of certain proteins inhibits biological activity (O'Sullivan 1973). After work by both Kendrick (1959) and Kubiena (1953) on the development of mor humus and decompositonal profiles, O'Sullivan (1973) suggests that mor humus possesses certain qualities which are likely to lead to the preservation of pollen within a stratified deposit. O'Sullivan (1973) also acknowledges the potential problems that are inherent in the use of mor humus for pollen analysis, firstly that the preservation of pollen grains may be poor due to fungal activity at the time of deposition within the leaf litter, soil fauna destruction of pollen, oxidation of pollen grains. Selective destruction of pollen grains can occur as a result of fungal and oxidation processes (Cushing 1967, Havinga 1963, 1964, 1967, Sangster and Dale 1961, 1964). Secondly the potential for destruction of the stratification of deposits is likely due to disturbance of the soil profile, for example wind-throw of trees or trampling. Finally, there is the potential for down-washing of humic material. However Bradshaw (2007) proposes that little or no mixing of pollen grains actually occurs as a result of this process, due to the potential for pollen to be trapped in aggregates of humic material. As previously discussed, radiocarbon dating of mor humus profiles can be difficult due to the mobility of soluble organic acids.

Down-washing is likely to occur in soil profiles and subsequent mixing of material, but Andersen (1997) suggests that where pollen concentrations are high, information about past vegetation can still be extracted.

2.8.2 Stand-scale investigations in the British Isles

The use of stand-scale palynology is extensive in many north western parts of Europe; in Denmark (Iversen 1964, Aaby 1983, Hannon *et al.* 2000), Poland, (Mitchell and Cole 1998), Scandinavia (Andersen 1984, Bradshaw and Hannon 1992, Bradshaw 1993, Björkman and Bradshaw 1996, Björkman 1997, Lindbladh and Bradshaw 1998, Lindbladh 1999, Lindbladh *et al.* 2003) and Northern America (Bradshaw and Webb 1985; Calcote 1995; Davis *et al.* 1998; Parshall and Calcote 2001; Schauffler and Jacobson 2002). However stand-scale investigations in the British Isles appear to be limited.

Stand-scale palynological investigations in the British Isles began in the early 1980's. Bradshaw (1981b) used pollen analysis from a small forest hollow located in Oxborough Wood, Norfolk. During his investigation he showed that detailed vegetation reconstruction from such sites is possible. His results supported the hypothesis that *Tilia cordata* was a major component of south eastern woods in England from approximately 5000 yrs BP to the anthropogenic reduction of the species. Bradshaw (1981b) was also able to use calibrated pollen data from this small forest hollow to estimate past tree basal-areas. A dated profile from Roudsea Wood, Cumbria was investigated by Birks (1982). This study spanned 6680 to 5150 yrs BP and presented information on the canopy composition of the mid-Flandrian forest around the hollow. In 1993, a 9500 year pollen record was obtained from Sidlings Copse, Oxfordshire (Day 1993). The sequence was used to investigate the antiquity of the woodland, assumed to be a primary ancient woodland (Day 1993). This work provided evidence that Sidlings Copse is actually an example of secondary woodland, but still of 'ancient' status (Day 1993).

Further studies took place in Ireland (Bradshaw and Hannon 1988; Hannon and Bradshaw 1989; Mitchell (1988, 1990a, 1990b). Mitchell (1988) used pollen data from small forest hollows in two woods in the Killarney Valley and compared this with regional pollen data. The record obtained represented at least the last 5000 years and revealed that the past woodland was more diverse than the present woodland. Mor humus profiles under closed canopy conditions were used again from Killarney by Mitchell (1990a) to investigate the impact of grazing and human disturbance on the dynamics of woodland in the area. Hannon and Bradshaw (1989) used Mor humus from two Connemara lake islands to test whether their woodland cover is primary woodland and also to investigate the dynamics of the woodland and succession change in a supposedly ungrazed system. Their findings indicated that neither locality had been continuously wooded over the past 1000 years and that tree colonization largely took place in the past 300 years.

In 1986 Mary Edwards identified at least four small forest hollow sites in four woodlands in Wales: Coed Ganllwyd NNR; Coed-y-Rhygen NNR; Coed Cymerau; and Coed Llenyrch. Her studies indicated that all of the woodlands had been disturbed in the past 300-400 years and that it is likely that at least one of the sites was once more open. She also used these data to suggest that it was not likely that these woodlands were primeval wildwood relicts, but modified natural forest stands or, stands which had regenerated on sites of older woodland.

2.9 References

Aaby, B. (1983) Forest development, soil genesis and human activity illustrated by pollen and hypha analysis of two neighbouring podzols in Draved Forest, Denmark. *Danmarks Geologiske Undersøgelse* II, **114**, 1-114.

Andersen, S. T. (1984) Forests at Løvenholm, Djursland, Denmark,at present and in the past. *Det Kongelige Danske Videnskabernes Selskabs Biologiska Skrifter*, **24**, 1-208.

Andersen, S.T. (1970) The relative pollen productivity of trees and its significance for the interpretation of a pollen diagram from a forested region. In Birks, H.J.B. and West, R.G. (eds) *Quaternary plant ecology*, Blackwell, Oxford, 109-115.

Andersen, S.T. (1997) Pollen analyses from Early Bronze Age barrows in Thy, *Journal of Danish Archaeology*, **13**, 7-17.

Anderson, R.S., Smith, S.J. (1997) The sedimentary record of fire in montane meadows, Sierra Nevada, California, USA: a preliminary assessment, In Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (ed.) *Sediment Records of Biomass Burning and Global Change, NATO ASI Series I: Global Environmental Change*, **51**, Springer, Berlin, 313-328.

Baker, C.A., Moxey, P.A., Oxford, P.M. (1978) Woodland continuity and change in Epping Forest, *Field Studies*, **4**, 645-669.

Barber, K.E., Twigger, S.N. (1975) Vegetational history of the New Forest: a preliminary note, *Proceedings of the Hampshire Field Club and Archaeological Society*, **30**, 5-8.

Barkham, J.P. (1978) Pendunculate Oak Woodland in a Severe Environment: Black Tor Copse, Dartmoor, *Journal of Ecology*, **66**,3, 707-740.

Birks, H.H. (1970) Studies in the vegetational history of Scotland, A pollen diagram from Abernethy Forest, Inverness-shire, *Journal of Ecology*, **58**, 827-846.

Birks, H.J.B. (1982) Mid-Flandrian Forest History of Roudsea Wood National Nature Reserve, Cumbria, *New Phytologist*, **90**, 2, 339-354.

Birks, H.J.B. (1996) Contributions of Quaternary palaeoecology to nature conservation, *Journal of Vegetation Science*, **7**, 89-98.

Birks, H.J.B. (2005) Mind the gap: how open were European primeval forests?, *Trends in Ecology and Evolution*, **20**, 4, 154-156.

Björkman, L. (1997) The history of Fagus forest in southwestern Sweden during the last 1500 years, *Holocene*, **7**, 419–432.

BjörkmanL., Bradshaw, R.H.W. (1996) The immigration of Fagus sylvatica L. and Picea abies (L.) Karst into a natural forest stand in southern Sweden during the last 2000 years, *Journal of Biogeography*, **23**, 235-244.

Bower, B. (1997) German mine yields ancient hunting spears, *Science news*, **151**, 9, 134.

Bradshaw, R.H.W. (1981a) Modern pollen representation factors for woods in south-east England, *Journal of Ecology*, **69**, 45-70.

Bradshaw, R.H.W. (1981b) Quantitative reconstruction of local woodland vegetation using pollen analysis from a small basin in Norfolk, England, *Journal of Ecology*, **69**, 941-955.

Bradshaw, R.H.W., Webb, T. (III) (1985) Relationships between contemporary pollen and vegetation data from Wisconsin and Michigan, USA, *Ecology*, **66**, 3, 721-737.

Bradshaw, R.H.W. (1988) Spatially-precise studies of forest dynamics, In Huntly, B., Webb, T, (eds) *Vegetation history*, Kluwer Academic Publishers, Dordrecht, 725-751.

Bradshaw, R.H.W., Hannon, G.E. (1988) Human influence in the decline of the Irish forest ecosystem, In Salbitano, F. (eds) *Human influence on forest* *ecosystems development in Europe*, ESF FERN-CNR, Pitagora Editrices, Bologna, 21-30.

Bradshaw, R.H.W., Webb, T. (III) (1990) Relationships Between Contemporary Pollen and Vegetation Data from Wisconsin and Michigan, USA, *Ecology*, **66**, 721-737.

Bradshaw, R.H.W. & Zackrisson, O. (1990) A two thousand year history of a northern Swedish boreal forest stand, *Journal of Vegetation Science*, **1**, 519-528.

Bradshaw, R. H. W., and G. E. Hannon. (1992) Climatic change, human influence and disturbance regime in the control of vegetation dynamics within Fiby Forest, Sweden. *Journal of Ecology*, **80**, 625-632.

Bradshaw, R.H.W. (1993) Tree species dynamics and disturbance in three Swedish boreal forest stands during the last two thousand years, *Journal of Vegetation Science*, **4**, 6, 759-764.

Bradshaw, R.H.W. (2002) Book Review: Grazing Ecology and Forest History, By F.W.M. Vera, *Forest Ecology and Management*, **165**, 327-329.

Bradshaw, R.H.W., Hannon, G.E., Lister, A.M. (2003) A long-term perspective on ungulate-vegetation interactions, *Forest Ecology and Management*, **181**, 267-280.

Bradshaw, R.H.W. (2007) Stand-scale palynology, Elias, S.A., (eds), *Encyclopaedia of Quaternary Science*, Elsevier, 2535-2543.

Brown, A.D. (2010) Pollen analysis and planted ancient woodland restoration strategies: a case study from the Wentwood, southeast Wales, UK. *Vegetation History and Archaeobotany*, **19**, 79-90.

Buckland, P.C. (2005) Palaeoecological evidence for the Vera hypothesis, *Large herbivores in the wildwood and in modern naturalistic grazing systems*, English Nature, Peterborough.Burleigh, R. (1981) W.F. Libby and the development of radiocarbon dating, *Antiquity*, **55**, 96-98.

Calcote, R. (1995) Pollen source area and pollen productivity: evidence from forest hollows, *Journal of Ecology*, **83**, 591-602.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Frechette, B., Gauthier, S., Prairie, Y.T. (2001) Change of fire frequency in eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? *Journal of Ecology*, **89**, 6, 930-946.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L., Williams, D. (1983) *Fire in forestry: volume I: forest fire behaviour and effects*, John Wiley and Sons, New York.

Clark, R.L. (1982) Point count estimation of charcoal in pollen preparations and thin sections of sediment, *Pollen et Spores*, **24**, 523-535.

Clark, R.L. (1984) Effects on charcoal of pollen preparation procedures, *Pollen et Spores*, **26**, 559-576.

Clark, J.S. (1988a) Particle motion and the theory of stratigraphic charcoal analysis: source area, transport, deposition, and sampling, *Quaternary Research*, **30**, 67-80.

Clark, J.S. (1988b) Stratigraphic charcoal analysis on petrographic thin sections: applications to fire history in northwestern Minnesota, *Quaternary Research*, **30**, 80-91.

Clark, J.S., Hussey, T.C. (1996) Estimating the mass flux of charcoal from sedimentary records: effects of particle size, morphology, and orientation, *The Holocene*, **6**, 129-145.

Clarke, M.J., Barber, K.E. (1987) Mire development from the Devensian Lateglacial to Present at Church Moor, Hampshire, In Barber, E.D. (ed.) *Wessex and the Isle of Wight: field guide*, Quaternary Research Association, Cambridge, 23-32.

Clinton, B.D., Boring, L.R., Swank, W.T. (1993) Canopy gap characteristics and drought influences in oak forests of the Coweeta Basin, *Ecology*, **74**, 1551-1558.

Cruickshank, J.G. & Cruickshank, M.M. (1981) The development of humus-iron podsol profiles, linked by radiocarbon dating and pollen analysis to vegetation history. *Oikos,* **36,** 238-253.

Cumming, S.G. (2001) Forest type and wildfire in the Alberta boreal mixedwood: What do fires burn? *Ecological Applications,* **11,** 1, 97-110.

Cushing, E.J. (1967) Evidence for differential pollen preservation in Late Quaternary sediments in Minnesota, *Review of Palaeobotany and Palynology,* **4,** 87-101.

Cwynar, L.C. (1978) Recent history of fire and vegetation from annually laminated sediment of Greenleaf Lake, Algonquin Park, Ontario, *Canadian Journal of Botany,* **56,** 10-12.

Darwin, C. (1859) *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life,* John Murray, London.

Darwin, C. (1871) *The descent of man and selection in relation to sex,* John Murray, London.

Darwin, C. (1872) *The expression of emotions in man and animals,* John Murray, London.

Davis, M.B., Calcotle, R.R., Sugita, S., Takahara, H. (1998) Patchy invasion and the origin of hemlock-hardwoods forest mosaic, *Ecology,* **79,** 2641-2659.

Day, P. (1993) Woodland origine and ancient woodland indicators': a case-study from Sidlings Copse, Oxfordshire, UK, The Holocene, 3, 1, 45-53.

Durno, S.E., McVean, D.N. (1959) Forest history of the Beinn Eighe nature reserve, *New Phytologist,* **58,** 228-236.

Earle, C.J., Brubaker, L.B., Anderson, P.M. (1996) Charcoal in northcentral Alaskan lake sediment: relationships to fire and late-Quaternary vegetation history, *Review of Palaeobotany and Palynology,* **92,** 83-95.

Edwards, M.E. (1986) Disturbance Histories of Four Snowdonian Woodlands and Their Relation to Atlantic Bryophyte Distributions, *Biological Conservation,* **37**, 301-320.

European Charcoal Database, available at http://www.fireman-europe.com/ECD.html, accessed July 2010.

Faegri, K., Iversen, J., Krzywinski, K. (1989) *Textbook of pollen analysis,* Wiley, Chinchester.

Forestry Commission report (a) on *Phytophthora ramorum,* available at http://www.forestry.gov.uk/pramorum, accessed July 2010.

Forestry Commission report (b) on New insect pests, available at http://www.forestry.gov.uk/pdf/fhd_08Jun10_new_insect_pests.pdf/$FILE/fhd_08Jun10_new_insect_pests.pdf, accessed July 2010.

Global Palaeofire Working Group, available at http://www.gpwg.org/, accessed July 2010.

Grant, M.J. (2005) *The Palaeoecology of Human Impact in the New Forest,* (unpublished PhD thesis), University of Southampton.

Hall, S.A., Burke, I.C. (2006) Considerations for characterizing fuels as inputs for fire behaviour models, *Forest Ecology and Management,* **227**, 102-114.

Handley, W.R.C. (1954) Mull and Mor in relation to forest soils, *Forestry Communication Bulletin,* **23**.

Hannon, G.E., Bradshaw, R.H.W. (1989) Recent vegetation dynamics on two Connemara lake islands, western Ireland, *Journal of Biogeography,* **16**, 75-81.

Hannon, G.E., Bradshaw, R.H.W., Emborg, J. (2000) 6000 years of forest dynamics in Suserup Skov, a seminatural Danish woodland, *Global Ecology and Biogeography,* **9**, 101-114.

Havinga, A.J. (1963) A palynological investigation of soil profiles developed in cover sand, *Mededelingen Landbouwhogeschool Wageningengen,* **63**,1, 1-93.

Havinga, A.J. (1964) Investigation into the differential corrosion susceptibility of pollen and spores, *Pollen et Spores*, 6, 621-635.

Havinga, A.J. (1967) Palynology and pollen preservation, *Review of Palaeobotany and Palynology*, 2, 81-98.

Horn, S.P., Horn, R.D., Byrne, R. (1992) An automated charcoal scanner for palaeoecological studies, *Palynology*, 16, 7-12.

Innes, J.B., Simmons, I.G. (1988) Disturbance and diversity: floristic changes associated with pre-elm decline woodland recession in north east Yorkshire, In Jones, M. (ed) *Archaeology and the Flora of the British Isles, Oxford University Committee for Archaeology Monograph,* 14, 7-20.

Iversen, J. (1941) Land occupation in Denmark's Stone Age, *Danmarks Geologiske Forenhandlugen II*, 66.

Iversen, J. (1964) Retrogressive vegetational succession in the Postglacial, *Journal of Ecology*, 52 (supplement), 59-70.

Iversen, J. (1969) Retrogressive development of a forest ecosystem demonstrated by pollen diagrams from fossil mor, *Oikos supplement*, 12, 35-49.

Iversen, J. (1973) The development of Denmark's nature since the last glacial, *Danmarks Geologiske Unders. Ser.*, 7, 1-126.

Jacobson, G.L., Bradshaw, R.H.W. (1981) The selection of sites for palaeovegetational studies, *Quaternary Research*, 16, 80-96.

Janssen, C.R. (1966) Recent pollen spectra from the deciduous and coniferous-deciduous forests of northeast Minnesota: a study in pollen dispersal, *Ecology*, 47, 804-825.

Janssen, C.R. (1981) On the reconstruction of past vegetation by pollen analysis: a review. In Bharadwaj, D.C., Vishnu-Mittre and Maheshwari, H.K. (eds) *Fourth International Palynological Conference Proceedings Volume III*, Birbal Sahni Institute of Palaeobotany, Lucknow, 163-172.

Johnson, E.A. (1992) *Fire and vegetation dynamics: Studies from the North American boreal forest*, Cambridge University Press, Cambridge.

Keeley, J.E., Fotheringham, C.J. (2001) Historic fire regime in Southern California shrublands, *Conservation Biology*, **15**, 6, 1536-1548.

Kehr, K. (1983) Walden three: Ecological changes in the landscape of Henry David Thoreau, *Journal of Forest History*, **27**, 28-33.

Kendrick, W.B. (1959) The time factor in the decomposition of coniferous leaf litter, *Canadian Journal of Botany*, **37**, 907-912.

Kelly, M., Meentemeyer, P.K. (2002) Landscape dynamics of the spread of sudden oak death, *Photogram Eng Remote Sens*, **68**, 1001-1009.

Krawchuk, M.A., Cumming, S.G., Flannigan, M.D., Wein, R.W. (2006) Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest, *Ecology*, **87**, 2, 458-468.

Kubiena, W. (1953) *The Soils of Europe*, Thomas Murby and Co, London.

Laird, L.D., Campbell, I.D. (2000) High resolution Palaeofire signals from Christina lake, Alberta: a comparison of the charcoal signals extracted by two different methods, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **164**, 111-123.

Lindbladh, M., and R. H. W. Bradshaw. (1998) The origin of present forest composition and pattern in southern Sweden, *Journal of Biogeography*, **25**, 463–477.

Lindbladh, M. (1999) The influence of former land-use on vegetation and biodiversity in the boreo-nemoral zone of Sweden, *Ecography*, **22**, 485–498.

Lindbladh, M., M. Niklasson, and S. G. Nilsson. (2003) Longtime record of fire and open canopy in a high biodiversity forest in southeast Sweden, *Biological Conservation*, **114**, 231–243.

Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L. (2009) Climate and wildlife area burned in western U.S. ecoprovinces, 1916-2003, *Ecological Applications*, **19**, 4, 1003-1021.

Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H. (1998) A 9000 year fire history from the Oregon Coast Range, based on a high-resolution charcoal study, *Canadian Journal of Forest Research*, **28**, 774-787.

MacDonald, G.M., Larsen, C.P.S., Szeicz, J.M., Moser, K.A. (1991) The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices, *Quaternary Science Reviews*, **10**, 53-71.

Marlon, J., Bartlein, P.J., Whitlock, C. (2006) Fire-fuel-climate linkages in the northwester USA during the Holocene, *The Holocene*, **16**, 1059-1071.

Millspaugh, S.H.C, Whitlock, C. (1995) A 750 year fire history based on lake sediment records in central Yellowstone National Park, USA, *The Holocene*, **5**, 283-292.

Mitchell, F.J.G. (1988) The Vegetational History of the Killarney Oakwoods, SW Ireland: Evidence from Fine Spatial Resolution Pollen Analysis, *Journal of Ecology*, **76**, 2, 415-436.

Mitchell, F.J.G. (1990a) The impact of Grazing and Human Disturbance on the Dynamics of Woodland in S.W. Ireland, *Journal of Vegetation Science*, **1**, 2, 245-254.

Mitchell, F.J.G. (1990b) The History and Vegetation Dynamics of a Yew Wood (Taxus baccata L.) in S.W. Ireland, *New Phytologist*, **115**, 3, 573-577.

Mitchell, F.J.G. (1998) The investigations of long-term successions in temperate woodland using fine spatial resolution pollen analysis, In Kirkby, K.J., Watkins, C. (eds) *The Ecological History of European Forests*, CAB International, Oxford, 213-223.

Mitchell, F.J.G., Cole, E. (1998) Reconstruction of long-term successional dynamics of temperate woodland in Bialowieza Forest, Poland, *Journal of Ecology,* **86**, 1042-1061.

Mitchell, F.J.G. (2005) How open were European primeval forests? Hypothesis testing using palaeoecological data, *Journal of Ecology,* **91**, 168-177.

Mooney, S., Radford, K. (2001) A simple and fast method for the quantification of macroscopic charcoal in sediments, *quaternary Australasia,* **19**, 1, 43-46.

Mooney, S., Black, M. (2003) A simple and fast method for calculating the area of macroscopic charcoal isolated from sediments, *Quaternary Australasia,* **21**, 1, 18-21.

Moore, F.J.G., Webb, J.A., Collinson, M.E. (1991) *Pollen Analysis,* Blackwell Scientific Publications, Oxford.

Moore, J. (2000) Forest fire and human interaction in the early Holocene woodlands of Britain, *Palaeogeography, Palaeoclimatology, Palaeoecology,* **164**, 125-137.

Native Woodland Habitat Action Plan 2007, available at http://www.ukbap.org.uk/, accessed July 2010.

Odgaard, B.V. (1992) The fire history of Danish heathland areas as reflected by pollen and charred particles in lake sediments, *The Holocene,* **2**, 218-226.

Odum, H.T. (2003) Center for Wetlands at the University of Florida: Ecological Engineering, www.cfw.ufl.edu/, accessed July 2010.

Oliver, C.D., Larsen, B.C. (1990) *Forest Stand Dynamics,* McGraw-Hill, New York.

O'Sullivan, P.E. (1973) Pollen Analysis of Mor Humus Layers a Native Scots Pine Ecosystem, Interpreted with Surface Samples, *Oikos,* **24**, 2, 259-272.

Patterson, W.A., Edwards, K.J., Maguire, D.J. (1987) Microscopic Charcoal As A Fossil Indicator of Fire, *Quaternary Science Reviews,* **6**, 3-23.

Parshall, T., Calcote, R. (2001) Effecxt of pollen from regional vegetation on stand-scale forest reconstruction, *Holocene*, **11**, 1, 81-87.

Parsons, R.W., Prentice, I.C., Saarnisto, M. (1980) Statistical studies on pollen representation in Finnish lake sediments in relation to forest inventory data, *Annales Botanici Fennici*, **17**, 379-393.

Peterken, G.F. (1974) Developmental factors in the management of British woodlands, *Quaternary Journal of Forestry*, **68**, 141-149.

Peterken, G.F. (1977) Habitat conservation priorities in British and European woodlands, *Biological Conservation*, **11**, 223-236

Peterken, G.F. & Game,M. (1984) Historical factors affecting the number and distribution of vascular plant species in the woodlands of central Lincolnshire, *Journal of Ecology*, **72**,155-182.

Peterken, G.F. (1993) *Woodland Conservation and Management*, second ed., Chapham and Hall, London.

Peterken, G.F. (1996) *Natural Woodland*, Cambridge University Press, Cambridge.

Pickett, S.T.A., White, P.S. (1985) Patch dynamics: a synthesis, In Pickett, S.T.A., White, P.S. (ed.) *The Ecology of Natural Disturbance and Patch dynamics*, Academic Press, Orlando, 371-384.

Ponel, P. (1995) Rissian, Eemian and Würmian Coleoptra assemblages from La Grad Pile (Vosges, France), *Palaeoegeography, Palaeoclimatology, Palaeoecology*, **114**, 1-41.

Power, M.J. & Palaeofire Working Group (2008) Changes in fire regimes since the last Glacial Maximum: an assessment based on global synthesis and analysis of charcoal data, *Climate Dynamics*, **30**, 887-907.

Quine C (2003) Wind as a disturbance agent and its implications for forest landscape patterns at Glen Affric. In: Bell S (ed) *The potential of applied* *landscape ecology to forest design planning*. Forestry Commission, Edinburgh, 55–62

Shore, J.S., Bartley, D.D., Harkness, D.D. (1995) Problems encountered with the ^{14}C dating of peat, *Quaternary Science Review*, **14**, 373-383.

Spencer, J.W. & Kirby, K.J. (1992) An Inventory of Ancient Woodland for England and Wales, *Biological Conservation*, **62**, 77-93.

Svenning, J.C. (2002) A review of natural vegetation openness in north-western Europe, *Biological Conservation*, **104**, 133-148.

Rackham, O. (2003) *Ancient Woodland*, Castlepoint Press, Colvend.

Ramsay, C.B. (1995) Radiocarbon calibration and analysis of stratigraphy : The OxCal program, *Radiocarbon*, **37**, 2, 425-430.

Ratcliffe, D.A. (1968) An ecological account of Atlantic bryophytes in the British Isles, *New Phytologist*, **67**, 365-439.

Ratcliffe, D.A. (ed.) (1977) A Nature Conservation Review, Cambridge University Press, Cambridge.

Rhodes, T.E., Davies, R.B. (1995) Effects of late Holocene forest disturbance and vegetation change on acidic Mud Pond, Maine, U.S.A., *Ecology*, **76**, 734-746.

Roberts, N. (1998) *The Holocene*, 2nd ed. Blackwell Publishing, Oxford.

Rose, C.I. (1979) Observations on the ecology and conservation value of native and introduced tree species, *Quarterly Journal of Forestry*, **73**, 219-229.

Sangster, A.G., Dale, H.M. (1961) A preliminary study of differential pollen grain preservation, *Canadian Journal of Botany*, **39**, 35-43.

Sangster, A.G., Dale, H.M. (1964) Pollen grain preservation: under represented species in fossil spectra, Canadian *Journal of Botany*, **42**, 437-449.

Schauffler, M., Jacobson, G.L. (2002) Persistence of coastal spruce refugia during the Holocene in northern New England, USA, detected by stand-scale pollen stratigraphies, *Journal of Ecology*, 90, 235-250.

Siipi, H. (2004) Naturalness in Biological Conservation, *Journal of Agricultural and Environmental Ethics*, 17, 457-477.

Simmons, I.G. (1964) Pollen diagrams from Dartmoor, *New Phytologist*, 63, 2, 165-180.

Simmons, I.G. (1965) The Dartmoor Oak Copses: observations and speculations, *Field Studies*, 2, 225-235.

Simmons, I.G. (1969) Pollen diagrams from the North York Moors, *New Phytologist*, 68, 807-827.

Simmons, I.G. (1975) Towards an ecology of Mesolithic man in the uplands of Great Britain, *Journal of Archaeological Science*, 2, 1-15.

Simons, I.G. (1996) *The Environmental Impact of Later Mesolithic Cultures*, Edinburgh University Press, Edinburgh.

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. (2007a) Theory of quantitative reconstruction of vegetation, I, Pollen from large sites REVEALS regional vegetation, *Holocene*, 17, 229-241.

Sugita, S. (2007b) Theory of quantitative reconstructions of vegetation, II, All You Need Is LOVE, *Holocene*, 17, 243-257.

Swain, A.M. (1973) A history of fire and vegetation in northeastern Minnesota as recorded in lake sediments, *Quaternary Research*, 3, 383-396.

Tauber, H. (1967) Investigations of the mode of pollen transfer in forested areas, *Pollen et Spores*, **13**, 615-621.

Tauber, H. (1965) Differential pollen deposition and the interpretation of pollen diagrams, *Dansmarks Geologiske Undersoglse Rakke* II, **89**, 69.

Tauber, H. (1977) Investigations of aerial pollen transport in a forested area, *Dansk botanisk Arkiv*, **32**, 1-121.

Théry-Parisot, I. (2002) Gathering of firewood during the Palaeolithic, In Thiébault, S. (ed.) *Charcoal Analysis: Methodological Approaches, Palaeoecological Results and Wood Uses*, Proceedings of the Second International Meeting of Anthracology, Paris, September 2000, BAR International Series, **1063**, Oxford, 243-249.

Thomas, R.C., Kirkby, K.J., Reid, C.M. (1997) The conservation of a fragmented ecosystem within a cultural landscape - the case of ancient woodland in England, *Biological Conservation*, **82**, 243-252.

UK Biodiversity Action Plan, available at http://www.ukbap.org.uk/ , accessed September 2010.

Van Geel, B., (1986) Application of fungal and algal remains and other microfossils in palynological analyses. In: Berglund, B.E. (Ed.), *Handbook of Holocene Palaeoecology and Palaeohydrology*. Wiley, Chichester, pp. 497–505.

Vera, F. W. M. (2000) Grazing ecology and forest history, p. 506. CAB International, Wallingford.

Viegas, D.X., Viegas, M.T.S.P., Ferreira, A.D. (1992) Moisture content of fine fuels and fire occurrence in central Portugal, *International Journal of Wildland Fire*, **2**, 69-86.

Viegas, D.X. (1998) Forest fire propagation, *Philosophical Transactions of the Royal Society of London Series A - Mathematical Physical and Engineering Sciences*, **356**, 1748, 2907-2928.

Waddington, J.C.B. (1969) A stratigraphic record of pollen influx to a lake in the Big Woods of Minnesota, *Geological Society of America, Special paper*, **123**, 263-283.

Watt, A.S. (1923-25) On the ecology of British beechwoods with special reference to their regeneration, *Journal of Ecology*, **11**, 1-48, **12**, 145-204, **13**, 27-73.

Weibel, P. (2009) *Modelling and assessing fire regimes in mountain forests of Switzerland*, unpublished PhD thesis, Dipl. Umwelt-Naturwissenschafter, ETH Zürich.

White, P.S. (1987) Natural disturbance, patche dynamics and landscape pattern in natural areas, *Natural Areas Journal*, **7**, 14-22.

Whitehouse, N.J. (2005) Forest fires and insects: palaeoentomological research from a subfossil burnt forest, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **164**, 231-246.

Whitlock, C., Larsen, C. (2001) Chapter 5: Charcoal As A Fire Proxy, In Smol, J.P., Birks, H.J.B., Last, W.M. (ed.) *Tracking Environmental Change Using Lake Sediments, Volume 3, Terrestrial Algal and Siliceous Indicators*, Kluwer Academic Publishers, Dordrecht, Netherlands.

Whitlock, C., Shafer, S.L., Marlon, J. (2003) The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management, *Forest Ecology and Management*, **178**, 1-2, 5-21.

Winkler, M.G. (1985) Charcoal analysis for palaeoenvironmental interpretation: a chemical assay, Quaternary Research, 23, 313-326.

Chapter 3

Loss of tree and shrub diversity in a western oakwood, NNR, Devon, UK

'How heavily that old wood sleeps in the sunshine; - not a leaf
Is twinkling, not a wing is seen to move
Within it; - but, below, a mountain-stream,
Conflicting with the rocks, is ever heard,
Cheering the drowsy noon. Thy guardian oaks,
My country, are thy boast – a giant race
And undergenerate still; but of those grove-
This pigmy grove, not one has clim'd the air,
So emulously that its loftiest branch
May brush the traveller's brow. The twisted roots
Have clasp'd, in search of nourishment, the rocks
And straggled wide, and pierced the stony soil: -
In vain, denied maternal succour, here
A dwarfish race has risen. Round the boughs
Hoary and feeble, and around the trunks,
With grasp destructive, feeding on the life
That lingers yet, the ivy winds, and moss
Of growth enormous. E'en the dull vile weed
Has fix'd itself upon the very crown
Of many an ancient oak; and thus, refused
By nature kindly aid, - dishonour'd – old-
Dreary in aspect – silent decays
The lonely Wood of Wistman!'
(N. T. Carrington, p. 55, 56, 1826)

3.1 Introduction

In this Chapter the origins of a origins of a western upland oakwood are investigated, building upon a significant amount of speculation as to the origins and 'upkeep' of Wistman's Wood. There are three upland oakwoods on

Dartmoor, all have been investigated to varying extents and using a variety of methodologies, however palaeoecological study of the woodland is limited to regional studies conducted by Simmons (1964, 1965, 1969) and Roberts and Gilbertson (1994). The hypothesis that the dominance of oak in these upland woodlands is a recent occurrence, happening hundreds of years ago and not thousands will be tested. The changing tree composition and balance of woodland and open communities (largely bog/heathland) species are described and the reasons for the dominance of oak in this area explored.

3.1.1 Ancient and semi-natural woodland

Peterken (1996) describes ancient woodland as a site which has been continuously wooded since AD 1600 in England and Wales and AD 1750 in Scotland. There are a variety of classifications within this designation, including those that refer to the naturalness or nativeness of the species within the woodland, these include semi-natural ancient woodland (ASNW) and planted ancient woodland (PAWS). Another classification is the proposed links with the post-glacial woodlands that covered much of Britain during the early Holocene. Primary ancient woodland is woodland that derives directly from the post-glacial woodlands, secondary woodland is woodland that originated on un-wooded ground prior to AD 1600. Ancient woodland sites have the potential to have a high species biodiversity and it has been proposed that certain plants occur predominantly in ancient woodland (Rackham 1980). The UK Biodiversity Action Plan considers these sites as habitats that contain species with particular adaptation to the conditions within ancient woodland (lack of major disturbance), and as a result are considered a priority for conservation, management and restoration.

3.1.2 Study Area

Dartmoor National Park is an area of moorland covering approximately 950km². In 1951 the area was designated a National Park and is now managed by Dartmoor National Park Authority, established in 1997. The park has been a designated area, The Forest of Dartmoor, since the 13th century when in 1240 AD the Sheriff of Devon was ordered to summon a jury of twelve knights to fix the boundary of the Forest by perambulation (walking or riding around the boundary from fixed points). In 1337, Edward III created the 'Duchy of Cornwall' to provide income for his heir, an estate that is still in existence today. There is a long history of military activity within the park boundary, in 1895 the Duchy of Cornwall granted the military a licence to test within the park, a practice that still continues to this day.

Its underlying geology consists of a large granitic mass, the largest of a chain of intrusions in the southwest peninsula of England. Much of the land is above 457m above sea level, the highest point being 615m above sea level. The granite is largely covered with blanket peat, with vegetation cover generally dominated by *Calluna, Molina* and *Eriophorum spp.* (Simmons 1964). Drier *Calluna* heath and acid grassland surround the areas of blanket bog, with the exception of some areas of semi-natural woodland, mainly of *Quercus robur* and mixed oak woodland and scrub, these areas are largely confined to the margins of the uplands (Simmons 1964). There are three upland oak copses in the granite area, one of which is Wistman's Wood. The general pattern of vegetation types and distribution on Dartmoor is likely to be the product of a long history of human occupation, agricultural and industrial use, and grazing management, superimposed upon changing soil and climatic conditions, (Barkham 1978).

3.1.3 History of the area and future management

Previous Ecological and Palaeoecological studies

Wistman's Wood is one of three upland oak woods on Dartmoor, the others being Pile Copse and Black Tor Copse. Each have provoked many years of interest, from speculation as to their origins and survival, to folklore attached to such unique places. Ecological interest heightened when it was realised that each woodland was dominated by *Quercus robur* and not *Quercus petraea*, the expected species in such climatic and edaphic conditions. Serious work on the woodlands began with writers in the Transaction of the Devonshire Association (Christy and Worth 1922; Harris 1921, 1938; Tansley 1939; Proctor 1962;

Barkham 1978), who attributed existence and survival of these woodlands to the clitter fields in which they grow. Clitter is the term used to describe the loose rock that cover hillsides as a result of the weathering of tors present within the landscape. The clitter allowed tree regeneration, by protecting and reducing the pressure on saplings from browsing, rubbing, tearing, and trampling by herbivores, by providing microclimates, and by creating favoured locations for the trapping, survival and germination of viable seed (Barkham 1978). However palaeoecological studies of the woodlands have been limited due to the lack of accumulation of suitable sediments in their immediate vicinity. Simmons (1964, 1965, 1969) used blanket bog records from the high moors to investigate the nature of vegetation within the Dartmoor area, however to truly investigate local scale change, palaeoecological information must be collected within the woodland. This has been limited due to the lack of sedimentation within the present woodlands, though one previous study has taken place in Pile Copse (Roberts and Gilbertson 1994).

Roberts and Gilberston (1994) used a small flush bog on an abandoned course of the River Erne, adjacent to Piles Copse, to investigate the relict status of the woodland. A core of 150cm was acquired and a series of twelve samples were analysed, with an estimated age of the core dating back approximately 2500 years. Their main findings were that there has been a recent phase of dominance of oak and that the history of the woodland is much more complicated than originally thought, finally concluding that the two anomalous phases of woodland in the diagram represent periods of planting.

Dendrochronological investigation of the woodland first took place as early as 1866, when an inscribing was left on the Buller stone, a large granite boulder near to the woodland, it read:

> 'By permission of H.R.H. the Prince of Wales, Wentworth Buller, on September 16th 1866, cut down a tree near this spot; it measured nine inches in diameter, and appeared to be about one hundred and sixty-eight years old'

However there is an earlier account made by Bray (1836) in relation to the analysis of a trunk taken from Wistman's Wood by Archdeacon Froude, which 'proved' that the woodland could not have been planted by Issabella de Fortibus, Countess of Devon, as 'by the aid of a microscope, he had counted about seven hundred' rings.

More recent analysis by Mountford *et al.* (2001) suggest that there are three generations of trees within the wood, the oldest 'A' generation appear to be between 200-400 years old and are likely to have originated within a degenerating oakwood.

Historical interest in Wistman's Wood

The appearance of Wistman's Wood has been recorded in every century since 1600. In 1621 Hockmore (in Barkham 1978) describes Dartmoor and the presence of a small wooded area called 'Welshman Wood', where 'the tallest tree is not much above the height of a man'. Carrington (1826) describes in some detail an excursion he took to 'Whistman's Wood' whilst he was completing his guide to Plymouth and Devonport in the early 1800's. Carrington (1826) describes a woodland similar to that which can be observed today, 'an assemblage of stunted oak-trees' of 'leafless moss-grown branches', described by Risdon (1714; in Carrington 1826) as 'some acres of woode the trees of which are a fathom about, and yet no taller than a man may touch the top with his hand'. There are also records of early 1900 geological excursions to the area, describing the difficulty parties had when trying travel through the woodland. It has been a woodland which has created much curiosity, both in terms of its past ecology and links to past woodland of Dartmoor, but also the folklore and mythology that is still spoken about to this day.

Perhaps one obvious point to explain is the changing nature of its name, from Welshman Wood to Whistman's Wood, to its present name, Wistman's Wood, this can be explained in part by the changing nature of the English language throughout the centuries, but there are also links to the myths attached to the woodland. Bray (p.73, 1836) proposes that its name is likely to be linked with the Druid activity within the wood as she links 'Wist' to the German 'to know', leading to the suggestion that the name means 'the wood of wisemen' and she supports this by the reasoning that the Druids were the 'philosphers or wise men of the Britons' and therefore the wood may have been an important place of assembly. This can potentially be supported by the presence of 'The Druids Stone' or 'Bullers Stone', an inscribed stoned near to the wood. Crossing (1987) proposes that the wood's 'Welshman' name may be attributed to the name coming from the Saxon word for the native Devonians, namely 'Wealas', a term generally applied to any native Briton at that time, who were concentrated in Wales, therefore the name was corrupted to 'Welshman'. Finally, Spooner (1967) proposes that the name is derived from the Devonshire word, 'Wisht', meaning pixie-led or haunted, a common superstition attached to the wood.

What can be drawn from years of historical interest and myth attached to Wistman's Wood, is that the woodland has been in existence for at least 400 years and that there is even the possibility that it was recorded and is in the same state as it would have been just after the Norman conquest, a comment made with reference to the perambulation immediately after the Norman invasion. Indeed these myths and legends may even be the reason for the continued existence of these upland oakwoods on Dartmoor (Simmons 1964).

Future/present management of the SSSI

The larger Wistman's Wood National Nature Reserve (NNR) is managed by Natural England and is in place to protect the four habitats present in the NNR, upland semi-natural woodland, upland acid grassland, blanket bog and dry upland heath. The upland woodland is home to a number of rare flowering plants, mosses, liverworts and lichens. In fact one of the rarest lichens *Bryoria smithii* is found on only four trees in the woodland and a few in Black Tor Copse and nowhere else in Britain. It is acknowledged in the management plan (2010) that grazing pressure is likely to be beneficial, allowing ground flora and the shrub layer to recover and could possibly be stopped altogether to allow for regeneration of tree species. This has been investigated by the erection of a grazing enclosure in the woodland; however it was found that this would not necessarily promote regeneration. Barkham (1978) reveals that unpublished data from the Nature Conservancy Council (a precursor organisation of Natural England) suggests that oak in upland Dartmoor oakwoods behaves as a pioneer species, unable to establish itself from seed in its own shade, this too was supported by work by Shaw (1974).

Wistman's Wood also features in a variety of management strategies and habitat action plans. Firstly, the Devon Biodiversity and Geodiversity Action Plan (2009) in which upland oak woodlands in Devon are highlighted as being areas which require management to maintain their significant contribution to biodiversity in the county. Various species of mammals, birds, beetles, butterflies, moths, crickets, vascular plants, fungi, mosses and lichens are associated with oak woodland in Devon, some of which appear on the list of the 'Species of Principal Importance in England' (NERC Act, S.41) (Devon Biodiversity and Geodiversity Action Plan 2009). The Dartmoor Habitat Action Plan for Woodland (2009) and the Dartmoor National Park Woodland Strategy (2005-2010) also recognises the importance of oak woodland, including ancient, semi-natural and planted. There are a series of objectives that are outlined in the action plan (Dartmoor Habitat Action Plan for Woodland 2007), these endeavour to maintain and expand, where relevant, upland oakwood; also to ensure the continued existence of upland oakwoods by diversifying the age and species composition of such woodlands, therefore protecting current veteran trees; finally to restore native tree cover to areas of ancient woodland previously planted with conifers. Finally, in 2006 the 'Restoring Ancient Woodland' project came into existence, led by the Dartmoor National Park Authority. This project aims to assist landowners to restore and enhance their ancient woodland; establish new native woodlands; restore ancient woodland sites previously planted with non-native species and explore funding opportunities to restore ancient woodland sites, involving local communities in the process.

3.1.4 Pollen sample site

In 1964, Wistman's Wood was designated as a Site of Special Scientific Interest (SSSI) as it is believed to be a rare relict example of ancient high-level woodland on Dartmoor. Wistman's Wood (NGR: SX 613770; 50°34'35.34" N, 3°57'43.01"W) is one unit of a larger SSSI, consisting of four habitat units, three of which are classified by Natural England (2010) as 'Dwarf shrub-heath-upland', and one as 'Broadleaved, mixed and yew woodland – upland', the latter covers an area of 3.06ha out of the larger 263.9ha. The wood itself is situated on the lower west-facing slopes of the West Dart valley at an altitude of 380-435 metres above sea level and is 'an outstanding example of native upland oak woodland developed on soils derived from the hard rocks of western Britain', (SSSI notification, Natural England, 2010). It is located approximately 13 miles west southwest of Tavistock.

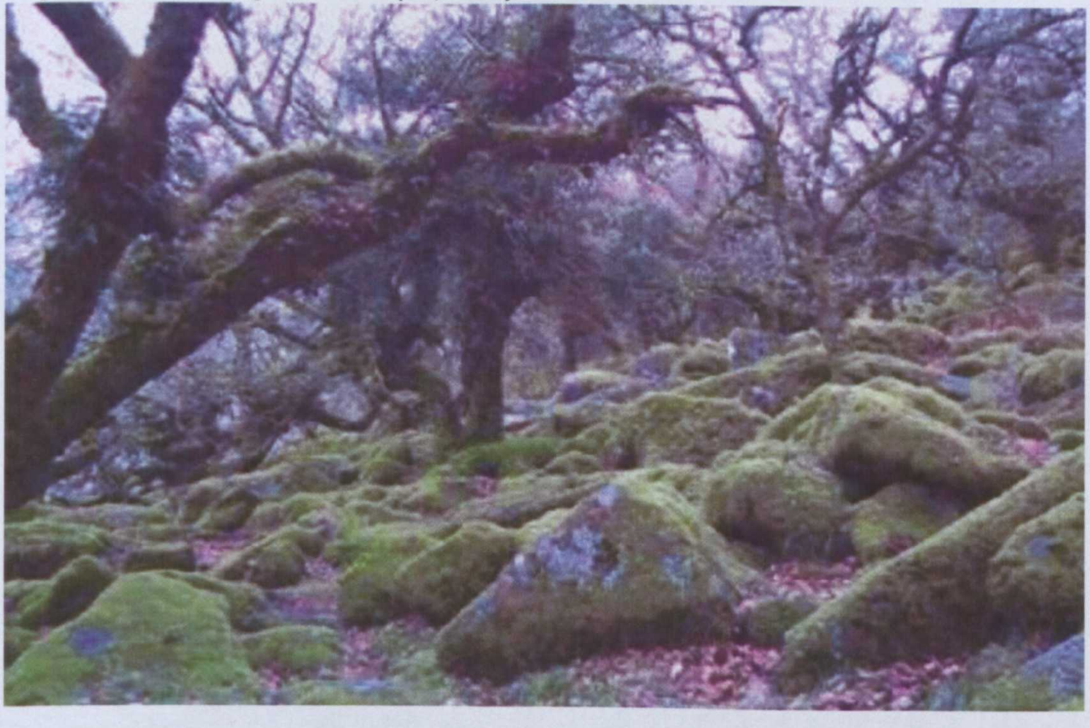
The woodland is dominated by Pendunculate Oak *Quercus robur* and the trees have a twisted and gnarled growth-form, as alluded to previously. Rowan *Sorbus aucuparia*, Holly *Ilex aquifolium* and Eared Willow *Salix aurita* have also been recorded. Ground flora is characterised by Bilberry *Vaccinium myrtillus*, Creeping Soft Grass *Holcus mollis*, Great Woodrush *Luzula sylvatica* and Bramble *Rubus fruiticosus* (Natural England Report, 2010). Fern flora within the wood is diverse and includes examples of filmy ferns. The epiphytic flora and lichens are well represented and can be observed covering many of the trees, Bryophyte mats also occur amongst the clitter.

Climatic conditions in the area are harsh, with high rainfall (approximately 2000mm p.a.), frequent mist, low cloud and strong winds. It is not possible to determine the variation in temperatures, humidity and wind speeds during the year (Barkham 1978), however Courtney and Hardy (1967) concluded that the climate around Wistman's Wood is what would be expected for a Westerly Maritime upland area.

The woodland floor consists of granite clitter, amongst which sediment has accumulated and many of the trees have established within these small, stable areas of sediment. The stability of the clitter is variable, some blocks move occasionally and others have recently moved, observed due to the lack of sedimentation within gaps. The variation in the woodland floor affects the ease with which grazing animals can move through the woodland, making some areas almost inaccessible, whilst others, toward the edges are more easily reached to graze.

Accumulation of fine grained organic sediments on the woodland floor occurs in small depressions defined by the position of granitic boulders and surface observation reveals a high concentration of leaf litter. The sediment within these depressions is classified as mor humus, which is a specific type of forest humus that is particularly good for the preservation of pollen grains, this is due to the low pH and the prevention of down-washing as the pollen grains become trapped in aggregates of humic matter. Mor humus is a dry, acidic accumulation of partially decomposed litter with very low biological activity (Bradshaw 2005).

Figure 3.1: Picture of Wistman's Wood, Dartmoor, UK, showing the clitter and deposits within depressions (C. Jones).



Hoover and Lunt (1952) define forest humus types using three criteria, a) presence or absence of an H layer ('a layer of organic rich material unrecognizable as to its origin'), b) the degree of incorporation of the organic matter with the upper mineral soil layer, and c) the structure, thickness and organic matter content of the H layer. The H layer is present in mor humus and there is practically no mixing of the organic matter with the mineral soil, with an abrupt transition from the organic matter to the underlying horizon.

Figure 3.2: a) Location of Dartmoor National Park indicated by red square; b) Location of Wistman's Wood NNR within the larger Dartmoor National Park, yellow areas indicate S.S.S.I.'s within Dartmoor (Natural England 2011); c) Wistman's Wood NNR and S.S.S.I., indicated by the light green area and number '2's (Natural England). Coring location indicated by red circle.

3.2 Methods

3.2.1 Coring technique

The location of the sample site was determined initially by the surface characteristics of the forest floor, i.e. an obvious collection of sediment between the granitic boulders present throughout the woodland. Care was taken however to avoid sites close to the edge of the wooded area due to the potential for disruption and mixing of deposits by grazing animals. Once a site was identified other criteria were investigated, i.e. depth of the sediment and the consistency and colour of the sediment retrieved using a small probing core. Ideally sediment depth should be approximately 50cm and dark in colour along with a sticky consistency, particularly towards the bottom, thus providing an increased likelihood of a high pollen concentration and likelihood of good preservation.

Figure 3.3: Photograph of core obtained from Wistman's Wood, Dartmoor, UK. (C. Jones).

The sample site chosen for this investigation was located mid-slope and approximately 15m from the southern tree boundary. A total of 37.5cm of sediment was collected from a small hollow, defined by granitic boulders on the forest floor. Due to the nature of the sample site, i.e. hollow size and depth, a Russian corer could not be used and as a result the entire length of the sediment was extracted using an improvised method. The method adopted involved the use of 2 half drain pipes pushed into the sediment, which were then secured in place and the surrounding sediment was removed to allow for the extraction of the core, (Figure 3.4). The core was kept in the drainpipes and placed in large polythene bags and kept upright to prevent contamination whilst being transported. The core was kept in the freezer prior to sampling.

Although no specific sediment stratigraphic analysis was conducted, there was a notable difference in the characteristics of the sediment within the core. These differences can be seen in a photograph of the sedimentary core (Figure 3.3). From the 0cm to 18cm the core contained notable plant macrofossils, however at 18cm the sediment characteristics change. The sediment becomes more organic rich, with no notable plant macrofossils and darkens in colour. There is also evidence of breakdown of surrounding in-organic material from the surrounding clitter, with small fragments of granite found within the sediment.

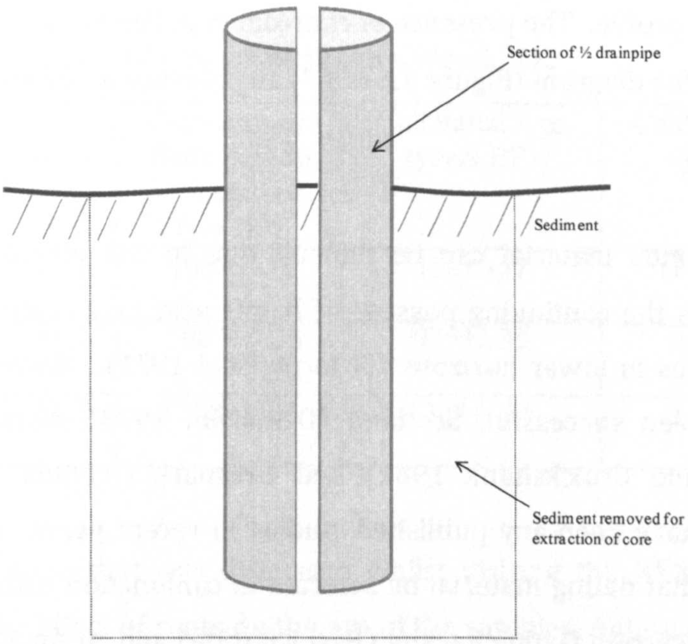


Figure3.4: Diagram of core extraction technique used in Wistman's Wood, U.K. (C. Jones).

3.2.2 Pollen analysis

Samples for pollen analysis ca. 1cm^3 in volume were taken m the 37.5cm core at a range of intervals throughout the core: 0-20cm at 4cm intervals; 20-33cm at 2cm intervals; 33-37cm at 1cm intervals. A total of 2 *Lycopodium* tablets were added to each sample to enable calculation of pollen concentrations. Samples were prepared in a similar method to that described in Moore *et al.* (1991) and included a Hydrofluoric acid treatment to remove siliceous material. Samples were mounted in glycerol jelly and stained with safranine. Pollen slides were traversed under the 400x magnification of Meiji microscope. A minimum of 400 pollen of terrestrial plants was counted at each level. Identifications were made with reference to the keys of Moore *et al.* (1991) and Faegri and Iversen (1989), and to modern material held in the Department of Geography, University of Liverpool. The state of preservation of unidentifiable pollen grains and spores was classified in terms of: crumpled; broken; degraded (Cushing 1967). Counts were tabulated using an Excel spreadsheet. The pollen diagram was plotted using Tilia Graph. The diagram was divided into zones by visual inspection, and they reflect key changes in vegetation composition throughout the profile. The presence of charcoal in pollen slides was noted and is indicated on the diagram (Figure 3.6 & 3.7) as presence or absence.

3.2.3 Chronology

Dating mor humus material can be difficult due to the mobility of soluble organic acids as the continuing passage of humic acid may rejuvenate the ^{14}C activity of humus in lower horizons (Scharpenseel 1971). However previous studies have been successful; Scotland (O'Sullivan 1973), Northern Ireland (Cruickshank and Cruickshank 1981) and Denmark (Iversen 1969), there appear not to have been any published studies in recent years. As a result it was proposed that dating material be selected in conjunction with scientists at the NERC Radiocarbon Dating Facility (East Kilbride) and, in April 2009, a visit was organised to the facility, where discussions and review of the material resulted in a successful outline of the methodology to be employed. The main concern was the effect of contemporary and recent root inclusion within the samples and potential effects upon the age of the samples. During the visit a significant amount of root material was removed from each sample.

Three $1cm^3$ samples were taken from the peat cores at a range of depths chosen to cover the length of the core and date significant events in the pollen diagram (Table 3.1). These samples were used for AMS radiocarbon dating of the humin fraction at the Radiocarbon Dating Facility, thus excluding potentially mobile fulvic and humic acids. Samples were digested in 2M Hydrochloric acid at 80°C for 8 hours, washed free from mineral acid with deionised water and then digested in 1M Sodium hydroxide at 80°C for 2 hours. The residue was rinsed free of alkali, digested in 2M Hydrochloric acid at 80°C for 2 hours, then rinsed free of acid, dried and homogenised. The total carbon was recovered as Carbon dioxide by heating with Copper oxide in a sealed quartz tube. The gas was converted to graphite by Iron/Zinc reduction. The graphite was then mounted on a pellet and the ^{14}C determined at the SUREC AMS facility on a 5MV National Electrostatic Corporation AMS system

Table 3.1: Radiocarbon dates for Wistman's Wood, U.K.

Publication Code	Depth (cm)	Conventional Radiocarbon Age (yrs BP)	Calibrated Age (years BP)	Calibrated Age (AD/BC)
SUERC-23850	21.1	106 +/-37	116+/-37	1835 +/-37
SUERC-23851	31.7	1067+/- 35	975+/-35	976+/-35
SUERC-23854	36.7	1208+/- 35	1208+/-35	817+/-35

A significant issue that was discussed whilst visiting the NERC Radiocarbon Facility was the effect of roots on the age of the samples. Although hand-picking of root material from the samples did not remove all root material, any residual root material that remained in the samples analysed for ^{14}C would likely not have a great effect on the ages of the samples (Garnett 2006, *personal communication*). Analysis showed that even if 10% of the sample that was processed for ^{14}C contained residual roots, the age of the samples would be up to 200 years older, based upon the assumption that the roots were contemporary at time of coring, i.e. AD 2006 (Garnett 2006). Communication with Dr. Garnett implies that the percentage of contemporary roots remaining in the sample would be far less than 10% of the sample, as hand-picking of root material prior to analysis only represented 3% of the total sample.

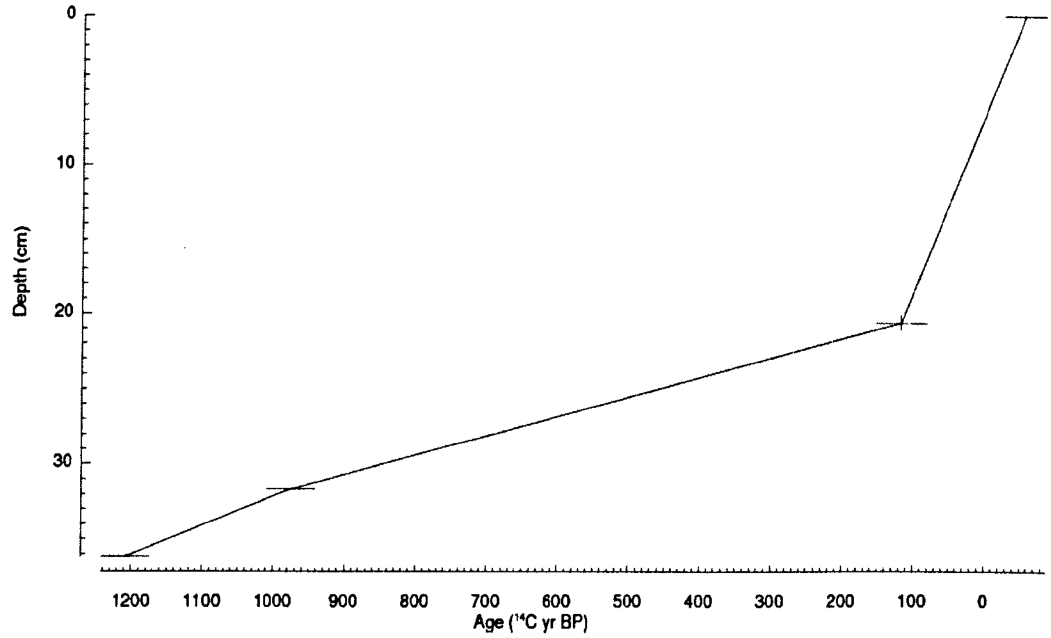


Figure 3.5: Linear age-depth model for Wistman's Wood, UK.

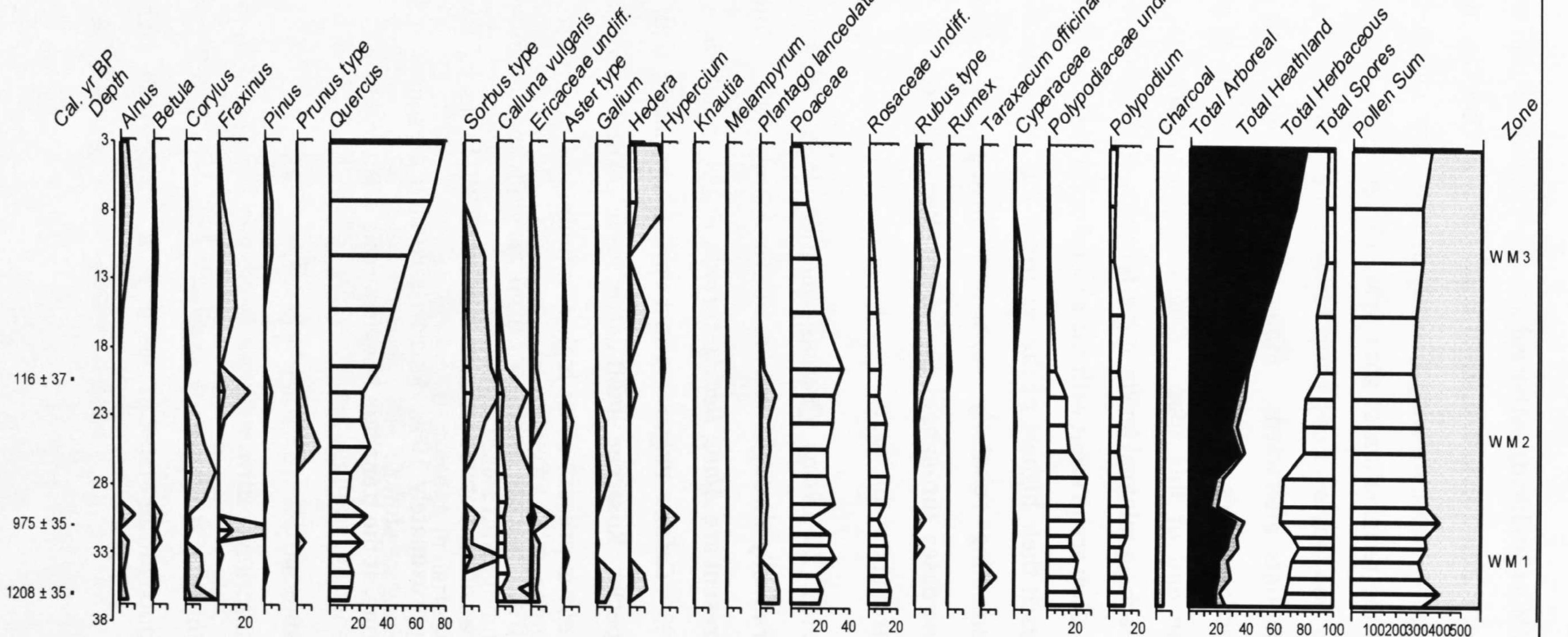
3.3 Results

WM1 (37.5-30cm): Arboreal pollen are dominated by *Quercus*, with some *Corylus*, *Betula*, *Alnus*, *Fraxinus*. *Quercus* representation fluctuates throughout this zone from ca. 10% to ca. 30%. *Calluna vulgaris* is present in largest percentage of the record, together with some Ericaeae. The *Calluna vulgaris* record gradually declines from approximately 10% to 5% throughout the zone towards the transition between zone WM1 and WM2 (Figure 3.6). Herbaceous species include Asteraceae, *Galium* and *Hypericum* together with significant amounts of Poaceae and Rosaceae undiff. *Plantago lanceolata* is present throughout the zone. *Polypodium* is present in significant numbers throughout. Micro-charcoal is recorded at each sample throughout the zone.

WM2 (30-20cm): Arboreal species diversity within this zone decreases, with both *Alnus* and *Betula* not represented. *Quercus* continues to dominate the arboreal taxa, showing a steady increase throughout, from 10% to almost 40% at the termination of zone WM2 (Figure 3.6). *Corylus* is present in the early section, however decreases towards the middle and is only present at minimal amounts afterwards. *Pinus* also makes an appearance towards the latter section of this zone. *Sorbus type* pollen percentage increases slightly towards the end of this zone. *Calluna vulgaris* decreases continually throughout; reaching minimal levels at the termination of zone WM2. Asteraceae type, and *Galium* are present with the second occurrence of *Hedera helix*. Poaceae levels reach their highest of the record at the termination of this zone, with levels remaining relatively consistent throughout. *Polypodium* representation decreases throughout the zone. Micro-charcoal is present at each sample throughout this zone.

WM3 (20-3.9cm): *Quercus* pollen dominates this zone, with values increasing gradually throughout from approximately 40% to 80%. Other arboreal taxa present are *Alnus*, *Betula*, *Corylus*, *Fraxinus* and *Pinus*, but levels do not exceed 5%. *Calluna vulgaris* is lost completely, along with many other herbaceous species. Rosaceae undiff decreases in amounts throughout (Figure 3.6). *Hedera helix* is present at its highest amounts of the record, with levels approaching 10%. Poaceae decreases from previous maximum levels of the record at the transition between zones WM2 and WM3, to its lowest value of the record, approximately 10%. Micro-charcoal is present in only one sample within the zone, at the transition between zone WM2 and WM3.

Figure 3.6: Pollen diagram for Wistman's Wood, Dartmoor, UK, plotted versus depth (cm). Values are represented as a percentage of the sample and charcoal presence is noted by a black dot at the sample depth. Species with patterned graphs have been exaggerated by a factor of 5.



3.4 Discussion

3.4.1 The vegetation history (Figure 3.7)

WM1 (600 AD - 1070 AD):

Quercus pollen dominates the arboreal species present in this zone, however other species present are at higher values than in the rest of the record, this may be an indication of a relatively open landscape, with some woodland species. The area is likely not to have been similar to that of the current woodland due to the presence of relatively high levels of herbaceous species and bog/heathland species. Due to the significant proportion of non-arboreal taxa to arboreal taxa, it is likely that the pollen deposited at the site is sourced from a larger area than under closed canopy conditions. Therefore the pollen diagram during this phase has a more regional influence in terms of taxa present. During this phase, *Calluna* is present in its highest amounts throughout the profile, supporting the likelihood of more open conditions with no significant woodland.

Forest Law was introduced soon after the Norman Conquest, leading to the protection of a large amount of animals within the forest, it also meant that enclosures of land were not permitted. This could result in an increase in the number of browsing animals and therefore impact upon the regeneration of the woodland resulting in an increase in open areas.

WM2 (1070 AD - 1850 AD):

The area still appears to be a mosaic of wooded areas dominated by *Quercus*, with a slight decrease in diversity, and open areas mainly dominated by bog species. The presence of significant herbaceaous and heathland species suggest that the site was not under closed canopy conditions and therefore pollen deposited again has a regional influence, as in WM1. However the proportion of arboreal pollen is increasing, which implies that there was a greater amount of woodland taxa growing in the vicinity. With the continuous decrease in *Calluna* throughout this phase it is likely to suggest that the influence of heathland species on the site is decreasing.

Grazing history of Dartmoor (Figure 3.10) suggests that there was significant grazing in the summer months (Barkham 1978). Significant levels of grazing in the area, as a result of the lifting of Forest Law in 1239, may have hindered tree regeneration and could have led to the decreased diversity of tree species and maintenance of open woodland. However the degree to which grazing could have affected Wistman's Wood is a topic of discussion, initial observations suggest that the clitter on which the wood is founded, would have protected seedlings from browsing animals and weather conditions. A possible explanation is that a combination of grazing and harsh climatic conditions during the 'Little Ice Age', could have resulted in unfavourable conditions for regeneration and therefore decrease in woodland species.

Anthropogenic activity on Dartmoor during this time period not only included the grazing of animals on the moor, but also the extraction of tin. This process required wood for smelting and meant that wooded areas were coppiced, including Black Tor copse and Piles Copse. Although recent studies (Mountford 2001) do not find significant evidence of coppicing within the woodland, it is possible that deadwood was collected and some trees were subject to coppicing. A similar period is identified at Piles Copse (Roberts 1994), however woody species are almost totally lost, Roberts attributes this to anthropogenic activity as it is unlikely that such a major loss of trees could be attributed to an extreme event such as a storm. Roberts (1994) implies that it was likely to be over-exploitation of the resources within the woodland that resulted in its loss. At Wistman's Wood it appears likely that anthropogenic activity, in terms of deadwood collection and small scale coppicing, but especially grazing, affected the number of individuals and size of the woodland, however parts still remained.

Figure 3.7: Pollen diagram for Wistman's Wood, Dartmoor, UK, plotted versus calendar years BP. Values are represented as a percentage of the sample and charcoal presence is noted by a black dot at the sample depth. Species with patterned graphs have been exaggerated by a factor of 5.

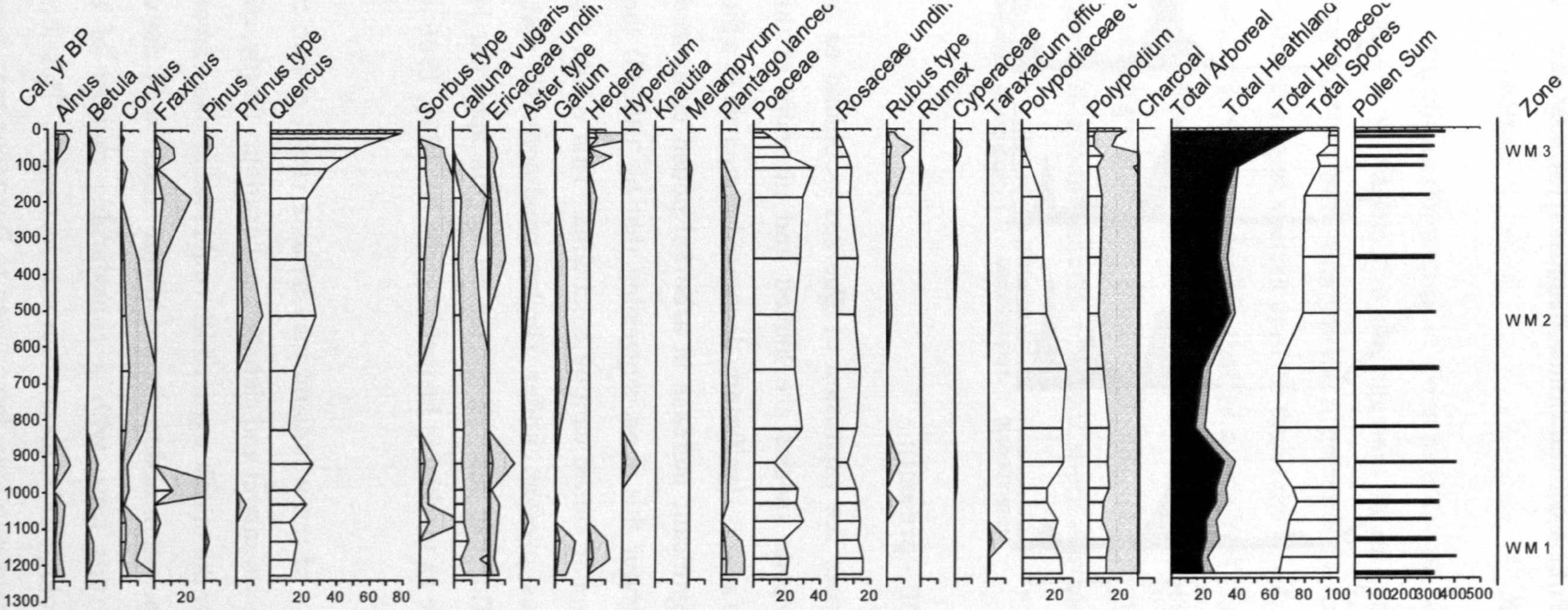
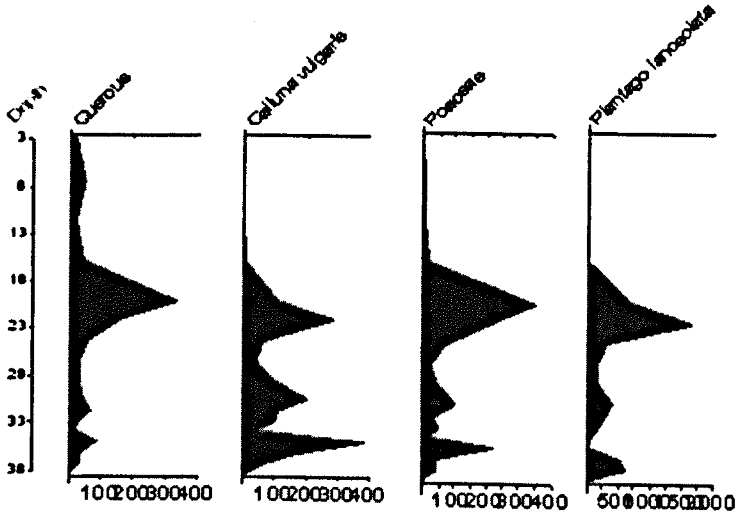


Figure 3.8: Pollen concentration diagrams for key taxa, Wistman's Wood, Dartmoor, U.K.



WM3 (1850 AD – present):

This period sees the expansion of *Quercus* woodland to conditions we see today, herbaceous species are limited and diversity of the woodland taxa present in the area is significantly decreased compared to a thousand years ago. There is a significant increase in arboreal pollen compared to herbaceaous pollen throughout this zone, suggesting that by 1850AD the coring site was likely to be under closed canopy conditions. This would also imply that the woodland was present, under similar conditions to that of the present woodland. This can also be evidenced by the apparent lack of change in woodland size as marked in historical maps for 1889, 1906 and 1954 (Figure 3.9a, b, & c).

The expansion of the woodland may be as a result of two factors; increased interest in the woodland and climatic amelioration. Firstly, climatic conditions improved after the middle ages, which could lead to more favourable conditions for tree regeneration within the woodland. Interest in the woodland is also significant at this time, with a considerable number of travellers to the woodland; ecologists; Victorian tourists; surveyors. This increase in interest and recent protection laws introduced to Dartmoor may have resulted in the protection of the woodland from previous harmful activities, such as excessive grazing in the late 19th Century.

It is possible that the significant dominance of *Quercus* in the present woodland could be due to some kind of selective management in the previous zone, potentially coppicing. The loss of diversity in the previous zone would result in a loss of species within the local species pool, to then take advantage of more favourable conditions. It is also possible that as a result of the removal of portions of woodland, what little soils is available, would be exposed to the high rainfall, leading to leaching of nutrients (Mitchell 1988). This could then result in a decrease in species, due to the inability for some species previously present at the site, not being able to grow on poor soils.

Figure 3.9a: Image of historical map of the Wistman's Wood area from 1889, with the wooded area outlined in red original 1:10560 scale map (sourced from Old-maps.co.uk, 2011).

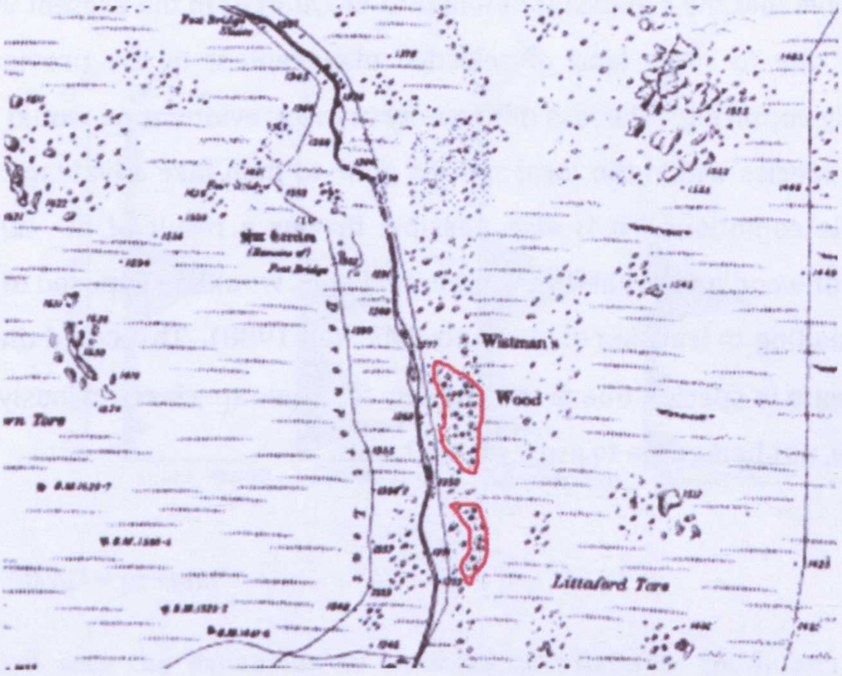


Figure 3.9b: Image of historical map of the Wistman's Wood area from 1906, with the wooded area outlined in red, original 1:10560 scale map (sourced from Old-maps.co.uk 2011).

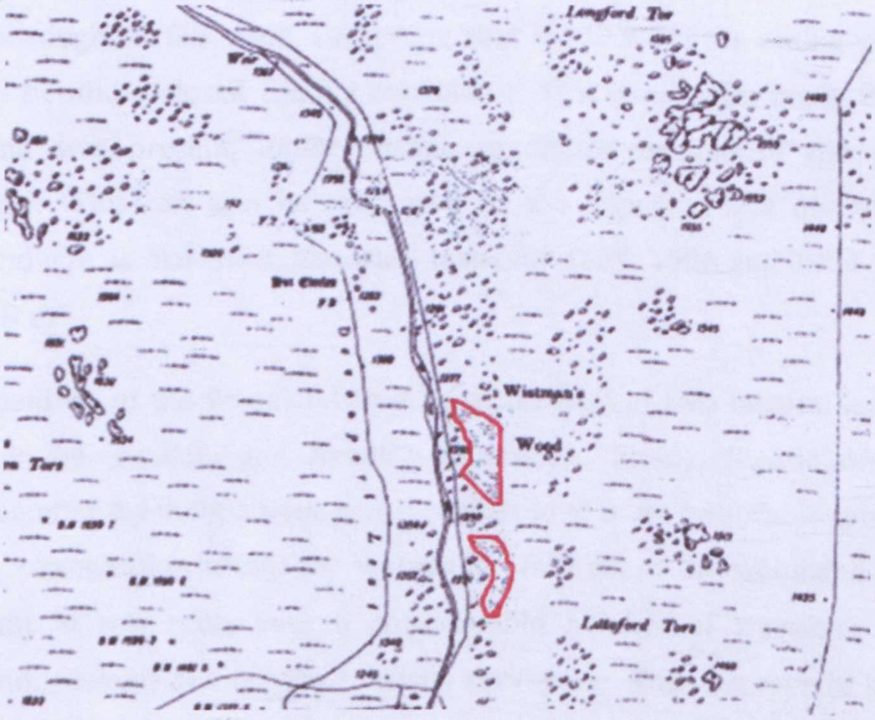
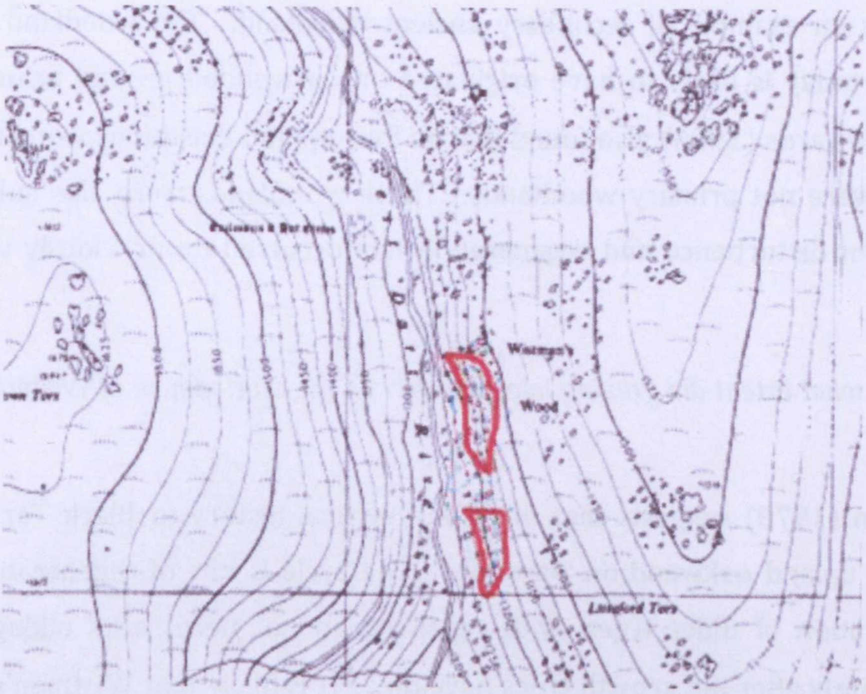


Figure 3.9c: Image of historical map of the Wistman's Wood area from 1954, original 1:10560 scale map (sourced from Old-maps.co.uk 2011).



3.4.2 Is Wistman's Wood an Ancient Woodland?

There is no simple answer to this question, however the continued existence of *Quercus* at the site implies that the woodland was not planted in the recent past, as is suggested by local folklore. Issabella de Fortibus is said to have planted the woodland during her time as Duchess of Cornwall, this is unlikely to have occurred as *Quercus* is present long before she was born.

Quercus is present throughout the diagram, most recently at much higher levels, therefore the current woodland structure is unlikely to be similar to that of the past. Mountford (2001) presents evidence of at least three generations of trees present in the contemporary woodland. Older generations are likely to be approximately 200-400 years old, the second oldest generation, 100 years old. The oldest generation therefore dates back further than the ancient woodland guidelines set out by Peterken (2008).

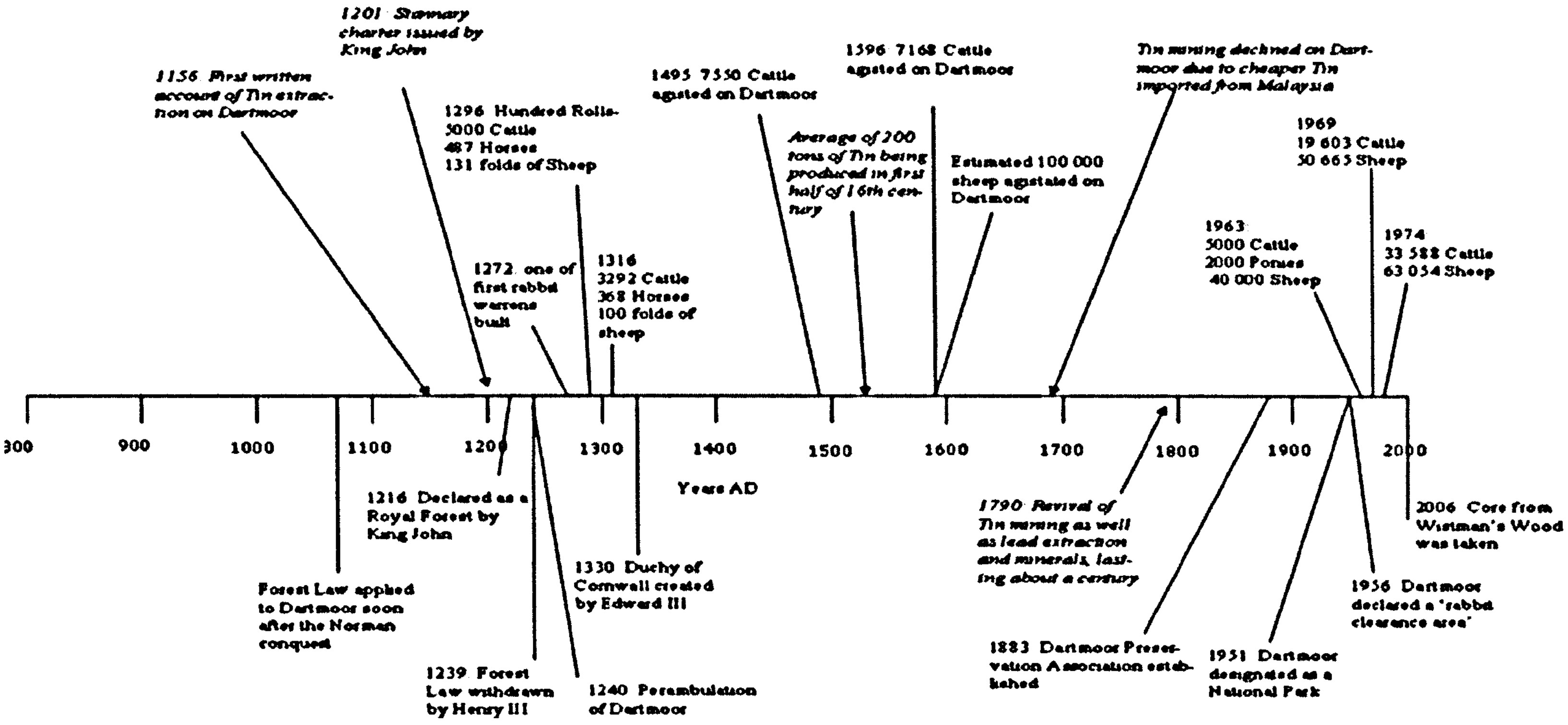
It also appears likely that wooded species were present since at least AD 800. However it is unlikely that the site was completely wooded due to the low representation of tree species compared to herbaceous species. In terms of the definition of primary or secondary woodland, it is very likely that Wistman's Wood is an example of secondary ancient woodland. The woodland that is present today is likely to have originated on un-wooded ground prior to AD 1650. Edwards (1986) also found that all four upland deciduous woodlands in Wales, were not primary woodlands. These woodlands were also subject to significant disturbance and regeneration had occurred on previously wooded sites.

3.4.3 To what extent did grazing have an effect on the development of Wistman's Wood

Barkham (1978) suggests that there is a cyclical history to Black Tor Copse, another upland oakwood on Dartmoor. The cycle is one of regeneration and deterioration of older trees, with regeneration not necessarily taking place immediately after old growth trees have died. It is likely that Wistman's Wood follows a similar regime.

It is very likely that grazing has affected the structure and composition of woodland in the past and indeed at present. There is documentary evidence for grazing in the area and effects of intense grazing in Wistman's Wood during the recent past. Archibald (1966) noted severely barked oak (*Quercus*) and rowan (*Sorbus*) trees during the severe winter of 1962-3, when sheep took shelter in the woodland. As previously noted, intense grazing pressure on mature trees can result in the death of individuals. It is also likely that grazing pressure may affect the regeneration of tree species due to animals browsing on seedlings. Barkham (1978) identified patches of oak (*Quercus*) less than 1m in height within bracken-dominated vegetation, with only saplings within the centre of these patches showing no evidence of browsing. This could support the hypothesis that the woodland regenerates in areas that are protected from grazing by unstable ground, clitter, and vegetation, bracken-dominated areas. Also noted by Barkham (1978), was the inability for oak (*Quercus*) to regenerate under its own canopy due to insufficient light intensity. A proposed model is that these upland oakwood stands have not grown in one fixed point and that in effect the stands move around the landscape as regeneration of young trees takes place, and deterioration of old growth trees occurs.

Figure 3.10: Timeline of selected activities on Dartmoor since AD 800 to present. These activities include change in management, grazing and exploitation of mineral resources (adapted from Simmons 1964, Barkham 1978).



3.4.4 Why is Quercus so dominant?

The dominance of oak (*Quercus*) at these upland woodland sites is of particular interest from ecologists. At Wistman's Wood it would appear that the dominance of oak (*Quercus*) was a recent occurrence, within the past ca. 400 years. Even if the pattern of regeneration of these stands is as is suggested by Barkham (1978) it is likely that woodland in the past was much more diverse than is presently observed. The palaeoecological evidence suggest that the woodland of AD 800 to AD 1100 was composed of oak (*Quercus*), birch (*Betula*), hazel (*Corylus*) and ash (*Fraxinus*).

Barkham (1978) suggests that the dominance of oak (*Quercus*) as a result of its apparent ability to act as a pioneer species in these environments. Roberts and Gilbertson (1994) conclude that the recent dominance of oak (*Quercus*) at Piles Copse is as a result of deliberate planting. It is likely that Barkham's (1978) describing oak (*Quercus*) as a pioneer species could explain its ability to establish itself in such harsh environmental conditions. However there is no definitive evidence of planting at Wistman's Wood. It could be suggested that selective management of the previously diverse woodland, in favour of oak (*Quercus*) by human activity in the area, could have resulted in the present dominance of oak (*Quercus*).

There are similarities between studies in Wales (Edwards 1986) and Ireland (Mitchell 1988). In Wales of the four atlantic bryophyte rich woodlands also found that the dominance of oak (Quercus) was a recent occurrence and was likely to be as a result of significant disturbance in the area, such as intensive coppicing and heavy grazing (Edwards 1986). Mitchell (1988) also found that the past vegetation composition of two oak (*Quercus)* dominated woodlands was once much more diverse. He also suggested that the present dominance of Quercus was as a result of successive disturbance and increased grazing pressures (Mitchell 1988). Mitchell (1988) also suggests that as a result of extensive disturbance would have resulted in a decrease in soil quality and therefore ability for many species previously present to regenerate. This too may be an explanation for the present dominance of oak (*Quercus*) at

Wistman's Wood. The climatic conditions at this site are similar to that of the Killarney valley and after significant disturbance, either caused by grazing or other anthropogenic activities, the soil would be exposed to high rainfall and subsequent leaching of the soil.

3.5 Conclusions

There have been limited investigations of the upland oakwoods on Dartmoor, Piles Copse, Black Tor Copse and Wistman's Wood. Palaeoecological investigation of the woodlands has been confined to an undated core from Piles Copse (Roberts and Gilbertson 1994). Vegetation history of Dartmoor has been investigated by Simmons (1963, 1964, 1969).

It would appear that the dominance of oak (*Quercus*) at Wistman's Wood and also Piles Copse (Roberts and Gilbertson 1994) is recent and that woodland at the site was previously more diverse. It is likely that a combination of grazing pressure, selective management of the woodland and climatic conditions have affected and resulted in the current vegetation structure. As Simmons (1964) concluded, human interference with the vegetation on Dartmoor cannot be disputed and so reasons for the existence of these remote, unique upland oakwoods is a question in itself. The folklore and ecological interest in Wistman's Wood for many centuries may have aided its preservation to this day.

This study has demonstrated that it is possible to use short mor humus profiles to investigate the palaeoecological characteristics successfully. It has also been shown that it is feasible to date mor humus profiles accurately, as this study provided the first dated mor humus core in recent years (according to published material).

Successful dating and pollen analysis of the mor humus core obtained from Wistman's Wood has provided information regarding the antiquity of the woodland, currently classed as an ancient woodland. It appears that Wistman's Wood is indeed ancient woodland, with significant proportions of wooded species prior to AD 1650 (Peterken 1996). However the likelihood of the woodland being an example of primary woodland is very slim, it is more likely that the woodland originated from an un-wooded area of land prior to AD 1650. This is supported by palaeoecological data which suggest that the area was much more open and potentially more 'wood-pasture'-like prior to AD 1650. This would therefore result in the continuity of woodland on the site being interrupted, a determining factor in the classification of primary or secondary woodland.

3.6 References

Archibald, J.F. (1966) Wistman's Wood: a Forest Nature Reserve, *Journal of the Devon Trust for Nature Conservation*, **11**, 423-428.

Barkham, J.P. (1978) Pendunculate Oak Woodland in a Severe Environment: Black Tor Copse, Dartmoor, *Journal of Ecology*, **66**,3, 707-740.

Bray,(Mrs) (1836) *Traditions, legends, superstitions and sketches of Devonshire on the borders of the Tamar and the Tavy: illustrative of the manners, customs, history, antiquities, scenery, and natural history: in a series of letters to Robert Southey*, **1**, John Murray, Albemarle-street, London.

Carrington, N.T. (1826) *Dartmoor, a descriptive poem, with notes by W. Burt*, 2nd edition, John Murray, Albemarle-street, London.

Courtney, F.M., Hardy, D.A. (1967) Wistman's Wood Forest Nature Reserve: a preliminary report of an ecological survey, *Journal of the Devon Trust for Nature Conservation*, **3**, 533-540.

Christy, M., Worth, R.H. (1922) The ancient dwarfed oakwoods of Dartmoor, *Report of the Devonshire Association*, **54**, 291-342.

Crossing, W. (1987) *Gems in a Granite Setting*, *Devon Books*, Exeter.

Cruickshank, J.G., Cruickshank, M.M. (1981) The Development of Humus-Iron Podsol Profiles, Linked by Radiocarbon Dating and Pollen Analysis to Vegetation History, *Oikos*, **36**, 2, 238-253.

Cushing, E.J. (1967) Evidence for differential pollen preservation in late Quaternary sediments in Minesota, *Review of Palaeobotany and Palynology*, **4**, 87-101.

Dartmoor Habitat Action Plan for Woodland (2009) available at http://www.dartmoor-npa.gov.uk/habitatactionplanforwoodland , accessed July 2009.

Dartmoor National Park Woodland Strategy (2005-2010) available at http://www.dartmoor-npa.gov.uk/laf-woodlandsstrategy , accessed July 2009.

Devon Biodiversity and Geodiversity Action Plan (2009) produced by the Devon Biodiversity Partnership, available at http://www.devon.gov.uk/dbap-invert-pinkseafan.pdf , accessed January 2010.

Discover Dartmoor, available at http://www.discoverdartmoor.co.uk/things-to-do/towns-villages.asp , accessed August 2010.

Edwards, M.E. (1986) Disturbance Histories of Four Snowdonian Woodlands and Their Relation to Atlantic Bryophyte Distributions, *Biological Conservation*, **37**, 301-320.

English Nature (2004) Map of Wistman's Wood, Dartmoor, U.K., produced by English Nature.

Faegri, K., Iversen, J., Kaland, P.E., Krzywinski, K. (1989) *Textbook of pollen analysis*, Wiley, Chinchester.

Grimm, E.C. (1991) *TILIA* and *TILIA GRAPH*, Illinois State Museum, Springfield.

Harris, G.T. (1921) Ecological notes on Wistman's Wood and Black Tor Copse, *Transactions of the Devonshire Association*, **53**, 232-245.

Harris, G.T. (1938) An ecological reconnaissance of Dartmoor, *Transactions of the Devonshire Association*, **70**, 37-55.

Hoover, M.D., Lunt, H.A. (1952) A key for the classification of forest humus types, *Soil Science Society Proceedings*, **368**.

Iversen, J. (1969) Retrogressive development of a forest ecosystem demonstrated by pollen diagrams from fossil mor, *Oikos supplement*, **12**, 35-49.

Mitchell, F.J.G. (1988) The Vegetational History of the Killarney Oakwoods, SW Ireland: Evidence from Fine Spatial Resolution Pollen Analysis, *Journal of Ecology*, **76**, 2, 415-436.

Moore, P.D., Webb, J.A., Collinson, M.E. (1991) *Pollen Analysis*, Blackwell Scientific Publications, Oxford.

Mountford, E.P., Backmeroff, C.E., Peterken, G.F. (2001) Long-term Patterns of Growth, Mortality, Regeneration and Natural Disturbance in Wistman's Wood, a High Altitude Oakwood on Dartmoor, *Transactions of the Devon. Associations for the Advancement of Science*, 133, 227-262.

Natural England Report (2010) Views about management, countryside and rights of way act 2000, schedule 11 (6), available at

http://www.naturalengland.org.uk/ourwork/conservation/designatedareas/nnr/1006174.aspx , accessed January 2010.

Natural England, accessed March 2011,

http://www.natureonthemap.naturalengland.org.uk/news.html,

NERC Act, S. 41, 'Species of Principal Importance in England' available at http://www.statutelaw.gov.uk/legResults.aspx?LegType=All+Legislation&title=Natural+Environment&Year=2006&searchEnacted=0&extentMatchOnly=0&confersPower=0&blanketAmendment=0&TYPE=QS&NavFrom=0&activeTextDocId=2321661&PageNumber=1&SortAlpha=0 , accessed July 2009.

O'Sullivan, P. (1973) Pollen analysis of mor humus layers from a native Scots pine ecosystem, interpreted with surface samples, *Oikos*, 24, 259-272.

Old-maps.co.uk, http://www.old-maps.co.uk, accessed March 2011

Peterken, G.F. (1996) *Natural Woodland*, Cambridge University Press, Cambridge.

Proctor, M.C.F. (1962) The epiphytic bryophyte communities of the Dartmoor oak woods, *Transactions of the Deveonshire Association*, 94, 531-554.

Restoring Ancient Woodland Project (2006) available at http://www.dartmoor-npa.gov.uk/index/aboutus/au-in-news/au-geninterestnews/au-2006-archive/au_rawnews2005.htm , accessed September 2009.

Roberts, C.A., Gilbertson, D.D. (1994) The vegetational history of Pile Copse 'ancient' oak woodland, Dartmoor, and the possible relationships between ancient woodland, clitter, and mining, *Proceedings of the Usher Society*, **8**, 298-301.

Scharpenseel, H.W. (1971) Radiocarbon dating of soils, *Soviet Soil Science*, 76-83.

Shaw, M.W. (1974) The reproductive characteristics of oak, In Morris, M.G., Perring, F.H. (ed.) *The British Oak: Its History and Natural History*, B.S.B.I. & E.W. Classey, Maidenhead, 162-181.

Simmons, I.G. (1964) Pollen diagrams from Dartmoor, *New Phytologist*, **63**, 2, 165-180.

Simmons, I.G. (1965) The Dartmoor Oak Copses: observations and speculations, *Field Studies*, **2**, 225-235.

Simmons, I.G. (1969) Environment and Early Man on Dartmoor, *Proceedings of the Prehistoric Society*, **39**, 203-219.

Spooner, G,M., Russell, F.S., (Hansford Worth, R.) (1967) *Worth's Dartmoor: compiled from the published work of the late R. Hansford Worth*, David and Charles, Newton Abbot (Devon).

SSSI notification, Natural England (2010), available at

http://www.naturalengland.org.uk/ourwork/conservation/designatedareas/nnr/1006174.aspx , accessed January 2010.

Tansley, A.G. (1949) *The British Islands and their Vegetation*, Cambridge University Press, London.

Chapter 4

Long-term basis for conservation and management of wood pasture in the Lower Wye Valley, U.K.

4.1 Introduction

This Chapter builds on the patchy historical documentation (Peterken 2008) of a small lowland bog located in the Lower Wye Valley, U.K, with a view to researching the origins of a degraded wood pasture habitat. I will describe the changing tree composition and balance between woodland and open communities during the late Holocene are described and constraining the age of origin for the wood pasture habitat. The hypotheses that the high local species diversity of the Cleddon Bog area is associated with long continuity of tree-cover and that the local wood pasture structure has an ancient origins tested. There are also likely to have been recent and significant changes in the balance of woodland and non-woodland cover. The role of burning often associated with land-cover change is examined, thereby exploring its role in the evolution of the wood pasture habitat.

The Wye Valley is an Area of Outstanding Natural Beauty (AONB), which straddles the southern borderlands between England and Wales, encompassing the lower 72km of the River Wye, totalling some 328km^2. The primary purpose of an AONB is to conserve and enhance natural beauty, while still practising limited, agriculture, forestry and other rural industries that fulfil the needs of local communities (Wye Valley management Plan 2009-2014). Cleddon Bog is one of forty-five Sites of Special Scientific Interest (SSSI) and in addition, there are three National Nature Reserves (NNR) in the greater Wye Valley AONB.

4.1.2 Ancient and semi-natural woodland

The term 'ancient woodland' is used to describe an area that has been continuously wooded since A.D. 1600 in England and Wales and A.D. 1750 in Scotland (Peterken 2008). Primary ancient woodland sites refer to woodlands that derive directly from post-glacial woodlands that covered much of Britain during the early Holocene (Brown 2010). The existence of primary woodland can only be confirmed by palaeoecological evidence; however this has been difficult to obtain due to the lack of suitable organic deposits within these ancient woodland sites. However, it is thought that much of British post-glacial woodland was cleared during the Bronze Age (ca. 2200-700 cal B.C.) (Roberts 2000) and as a result much of the ancient woodland that survives today, is likely to be of secondary origin, having regenerated on land previously occupied by primary woodland.

These ancient woodland sites can also be classified in terms of their 'naturalness', as much of the vegetation composition of the landscape has been altered by land-use changes. Semi-natural ancient woodland sites (ASNW) contain native tree species that have not obviously been planted. There are also areas of planted ancient woodland (PAWS), where native trees have been replaced to some extent with non-native tree species. Both types of ancient woodland are considered by the UK Biodiversity Action Plan (1995) as threatened habitats that contain species with particular adaptation to these sites (Pryor *et al.* 2002).

4.1.3 Wood pasture

Wood-pasture might be defined as 'tree-land on which farm animals or deer are systematically grazed' (Rackham 2004). This particular type of land-use category contains trees and shrubs and generally includes grazing of animals with occasionally other activities including acorn collection, grass cutting and field crop cultivation (Bergmeier *et al.* 2010). Such land-use systems have been present throughout Europe from prehistoric to present times (Mosquera-Losada *et al.* 2009). Wood-pasture systems differ between regions, in terms of species composition, structure and ecology, depending upon climate, soil, topography, geology and species-pool (Bergmeier *et al.* 2010).

In Britain, the Surrey Biodiversity Partnership (2008), revised the definition of wood-pasture with the aim of producing 'a practical set of working definitions for different types of wood-pasture systems (both upland and lowland) to guide implementation of the Habitat Action Plan (HAP)'. The partnership notes that wood-pasture systems occur much more widely and in more varied forms than has been previously appreciated. The Surrey Biodiversity Partnership (2008) defines wood-pasture systems as:

> 'Wood-pastures are areas that have been managed by a long-established tradition of grazing, allowing, where the site is in good condition, the survival of multiple generations of trees, characteristically with at least some veteran trees or shrubs. The tree and shrub component may have been exploited in the past and can occur as scattered individuals, small groups, or as more or less complete canopy cover. Depending on the degree of canopy cover other semi-natural habitats, including grassland, heath, scrub etc. may occur in mosaic with woodland communities. While oak, beech, alder, birch, ash, hawthorn, hazel or pine are often dominant, a wide range of other tree and shrub species may occur as part of a wood-pasture system.'

Differences in wood-pasture systems can also be attributed to history of land-use and current management of the area, making it difficult to clearly identify a wood-pasture system. However, most wood-pasture habitats can be termed as semi-natural (Begermeier *et al.* 2010).

Wood-pasture is of significant conservation interest as it generally includes a wide range of habitats, differing nutrient levels, contrast in shade and light conditions and differences in disturbance. Where old, veteran trees still remain in the complex, they can provide structural qualities common to both primeval and pasture woodland (Bergmeier *et al.* 2010), also providing the environmental conditions for the existence of beetles associated with primeval woodland (Müller *et al.* 2005). Diversity of a range of species is significant beetles (Desender *et al.* 1999; Taboada *et al.* 2006), snail diversity both at local and landscape scales (Labaune and Magnin 2002) and bird species (Tucker and Evans 1997).

However due to the need of land-use management for the existence of wood-pasture systems, there are a range of threats to these habitats in general relating to changes in land-use practices (Bergmeier *et al.* 2010). Wood-pasture exists as a mosaic of wooded and open areas, however if natural loss of old-growth trees is not compensated by subsequent regeneration, the result will be open pastures. Overgrazing of the wood-pasture system can be a contributing factor in the lack of regeneration of wooded species, with seedlings and juvenile trees being destroyed due to trampling or selective grazing of young trees and shrubs. The other extreme may be the abandonment of the wood-pasture system, leading to scrub encroachment and denser woodlands. The diversity of wood-pasture systems cannot simply be managed in terms of woodland or grassland management practices alone, conservation of wood-pasture habitats require long-term management (Bergmeier *et al.* 2010).

4.1.4 The Vera debate

In recent years management plans in the UK have taken note of the findings of Dutch ecologist Frans Vera (2000) who questioned the current understanding of the prehistoric wooded landscape and its relationship with fauna within that landscape. Vera (2000) hypothesises that the structure of the lowland forest was much more open than originally thought and that this openness was determined and controlled by the presence of large herbivores, in contrast to the high forest hypothesis, where large herbivore abundance is believed to be generally low with minimal impact on forest structure (Mitchell 2005). Vera proposed a four phase model in which vegetation structure is controlled by large herbivores who maintain a more open landscape with more open space and scrub than in the closed-canopy model and with a mosaic of patches of trees with open space or scrub. These phases comprise a) open/park phase: largely open landscape consisting of mainly heath and grassland; b) scrub phase: thorny scrubs across the landscape, providing protection for tree regeneration; c) grove phase: tree-dominated landscape where shade intolerant species cannot survive, resulting in a lack of regeneration of the woody species; d) break-up phase: opening of the landscape due to lack of regeneration of wooded species (Vera 2000).

However a number of critics of the hypothesis have suggested that this was not the case and that there were flaws in Vera's logic. Palaeoecological data from Ireland do not support the hypothesis, *Quercus* and *Corylus* pollen records were compared with regions that have supported large herbivores and areas where large herbivores were excluded (Ireland), similarity between these data sets implies that large herbivores were not required to maintain these taxa (Mitchell 2005). Bradshaw *et al.* (2003) outline the strengths and weaknesses of both the 'wood-pasture' hypothesis and high forest hypothesis. They suggest a compromise, where a range of disturbance mechanisms are considered, the impact of browsing animals is fully recognised and potential for a variety of mechanisms, such as fire, in conjunction with animal browsing, may have implications for vegetation structure.

4.1.5 Study area

The Trellech-Wentwood plateau is an area of high ground to the west of the Lower Wye valley. The plateau stretches north to Penalt and southwest along the Wentwood ridge toward the river Usk. It is bounded to the west by the Brownstone scarp, to the east it drops sharply to the Wye gorge. Short streams drain into the River Usk, including Cleddon Brook. To the south, the area is bounded by a change in geology from Devonian sandstones and bedstones, with quartz conglomerate on higher ground, to the ecologically significant Carboniferous Limestone (Peterken 2008). The Trellech-Wentwood Plateau is an area with a variety of 'distinctive features': Ancient semi-natural woodland

and planted ancient woodland sites; semi-natural grassland; heathland; bogs; the only one being Cleddon Bog; parkland and estate farmland; and remnant orchards (Wye Valley Management Plan 2009-2014).

The climate is oceanic with mild temperatures (mean temperatures in January 2-3°C and July 12-13°C at 300metres above sea level), high precipitation (ca. 750-1000 mm/yr) and frequent strong south and west prevailing winds (Sumner 1997).

4.1.6 History of the area and future management

Cleddon Bog is located in an area of the Trellech-Wentwood Plateau known as the Wyeswood common. Wyeswood common was a chain of wooded pastures that, in the medieval period, stretched along the Trellech-Wentwood Plateau (Peterken 2007). These included Wentwood, Earlswood, Coed Llyfos, Chepstow Park, Fedw and Wyeswood. However land-use practices in these areas have changed over the past 800 years, giving rise to changes in vegetation composition and structure. Earlswood and Coed Llyfos became largely denuded of trees, then cleared for agriculture; Wyeswood also lost most of its tree cover, however in recent years a substantial area has been turned into plantations (Peterken 2007). Some areas of ancient semi-natural woodland are still present, for example within the Wentwood (Brown 2010).

Wyeswood common is punctuated by various settlements, including Trelleck and other settlements and their associated enclosed farmland and woodland. In 1307 about 20-25% of the lordship's 16, 000 acres was exploited intensively for agriculture as arable, pasture and meadow, with the remaining land as woodland (Peterken 2007). The condition of Wyeswood changed over the centuries. In the 1300's the wooded areas appear to have been largely oak and beech, where coppicing and charcoal manufacture took place. Deer have grazed the common, being recorded in the 1382 Wyeswood Chase, also in 1576 and 1618, where cases were brought against deer poachers (Peterken 2007). In 1629, there was said to be no timber left in the Wyeswood Common area and in 1697 it was described as 'formally stocked with red deer and timber, but now wanting both' (Peterken 2007). However a change in management may have occurred, as by 1769 a survey records 1000 acres of underwood (Peterken 2007). The margins of the Wyeswood appear to be well-wooded, with records in 1676 of 2206 acres of common woodland and 1666 acres of private woodland (Peterken 2007). Peterken (2007) suggests that the core of the Wyeswood became ever more open and covered in heathy grassland, whilst the margins remained well-wooded. It appears that in the late 1700's and early 1800's a series of disputes occurred regarding enclosure of the Common and eventually in 1810 an Enclosure Act covered 4200 acres. However large areas remained unenclosed including Penalt, Trelleck Mitchell Troy, Tintern, Cwmcarvan, Llandogo and Llanishen (Peterken 2007) and most likely, the Cleddon Bog area.

In recent years, efforts have been made to restore the Wyeswood landscape to conditions similar to those of its wood-pasture phase. A small area of land has been purchased by the Gwent Wildlife Trust in an effort to create a wood-pasture landscape, similar to that which could be found on the Trellech Ridge up until the late 19th century. Various management strategies have been reviewed, however the favoured and adopted strategy has been 'rewilding', where the stock of grazing cattle will be kept at a level that will allow trees and shrubs to colonise and eventually establish a mosaic of woodland, scrub and open ground (Peterken 2007). This is also referred to as the Oostvardersplassen option, i.e. with reference to Vera's (2000) wood-pasture hypothesis of grazing ungulates affecting the structure of the landscape and maintaining its openness, whilst the lack of any other intervention would also allow regeneration of wooded and shrub species.

Cleddon Bog itself has also recently undergone an attempt to restore the rare heathland it contains. The heathland had slowly been invaded by Birch and Sallow trees, resulting in a gradual loss of important species of flora and fauna and a change in bog wetness. Only small patches of *Sphagnum* remain, and many species have been lost (Peterken 2008). Broad-leaved cottongrass (*Eriophorum latifolim*), round-leaved sundew (*Drosera rotundifolia*) and common butterwort (*Pinguicula vulgaris*) have not been seen since the 1970's. Woodland now grows along the stream where meadow thistle was recorded (Peterken 2008). These changes are thought to be as a result of a change in land-use, with common rights to pasture, turf, firewood and bracken still in existence, but not having been exercised since the early 1950's. Both heathland and mire used to be regularly burned to maintain pasture, however the last recorded burn was in 1968. In 2008, wooded species growing within the centre of the bog were removed, in an attempt to increase the openness of the bog and decrease the loss of rare bog species. This process will continue and monitoring of the bog for key species will determine if this process is successful.

4.1.7 Pollen sample site

In 1963, Cleddon Bog (Figures 4.1, 4.2) was notified as a Site of Special Scientific Interest (SSSI), for being the best example of a lowland bog habitat in the old vice-county of Monmouth and was declared a Local Nature Reserve in 1970. Cleddon Bog (NGR: SO5004, 51° 43'55"N, 02° 42'35"W) is a small bog, comprising approximately 15 ha of peatland, located within a wood pasture complex in the Lower Wye Valley at 230 metres above sea level. Located around 9km south of Monmouth, in south-east Wales. Cleddon Bog is believed to be the largest surviving example of heather/bilberry dominated heathland that covered much of the Trellech-Wentwood plateau (Howard and Woodman, in Wimpenny 2000). It is believed to be a remnant of the great Wyeswood Common and is still in existence today as a result of the lack of enclosure during the nineteenth century (Peterken 2008). The bog is surrounded by semi-natural deciduous woodland and coniferous plantations. There is little *Sphagnum* remaining on the bog today, which is largely dominated by purple moor-grass (*Molina caerulea*), along with cross-leaved heath (*Erica tetralix*), heather (*Ericaceae*) and hare's-tail cottongrass (*Eriophorum vaginatum* L.) (Peterken 2008). Parts of the bog have been colonised by birch and sallow. Previous accounts of the bog suggest a 'wet *Sphagnum* lawn in a matrix of well-grazed, treeless, wet heath until the mid-twentieth century', Peterken (2008).

Figure 4.1: Images of Cleddon Bog, Wye Valley, UK. a) Image of sample site (Photographed by C. Jones 2007); b) Photograph of heather in bloom amongst tussocks of purple moor-grass, (Peterken 2008).

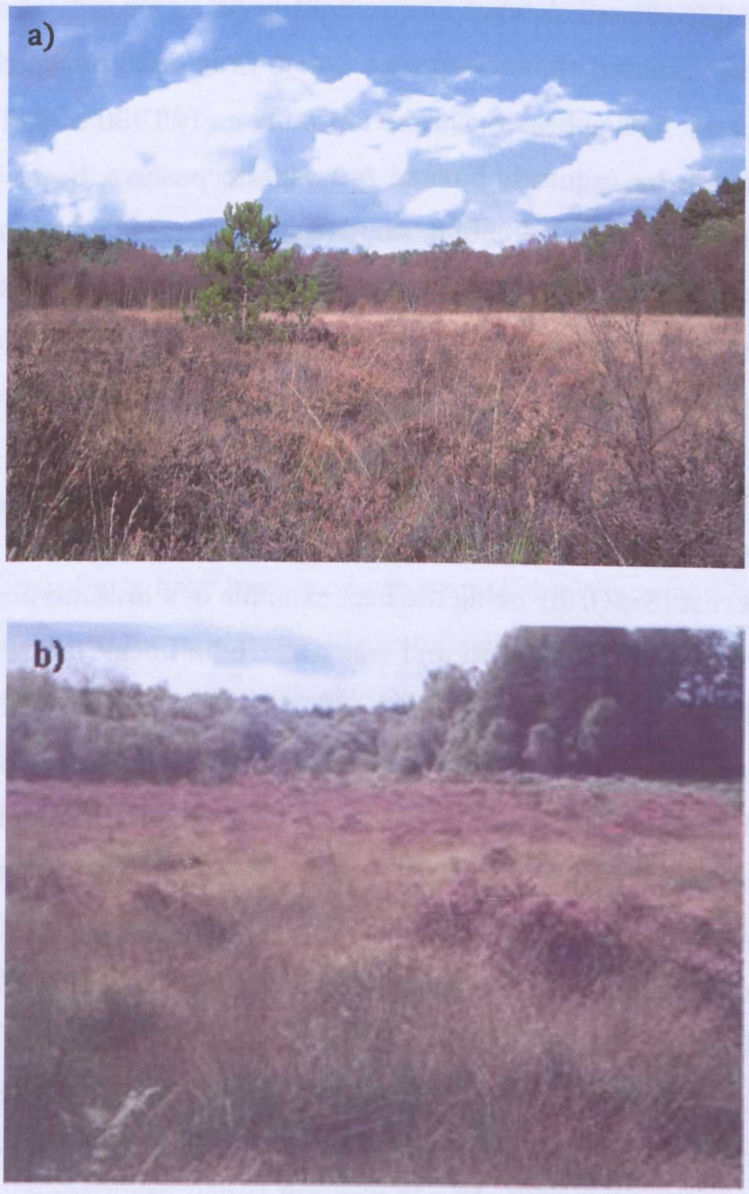
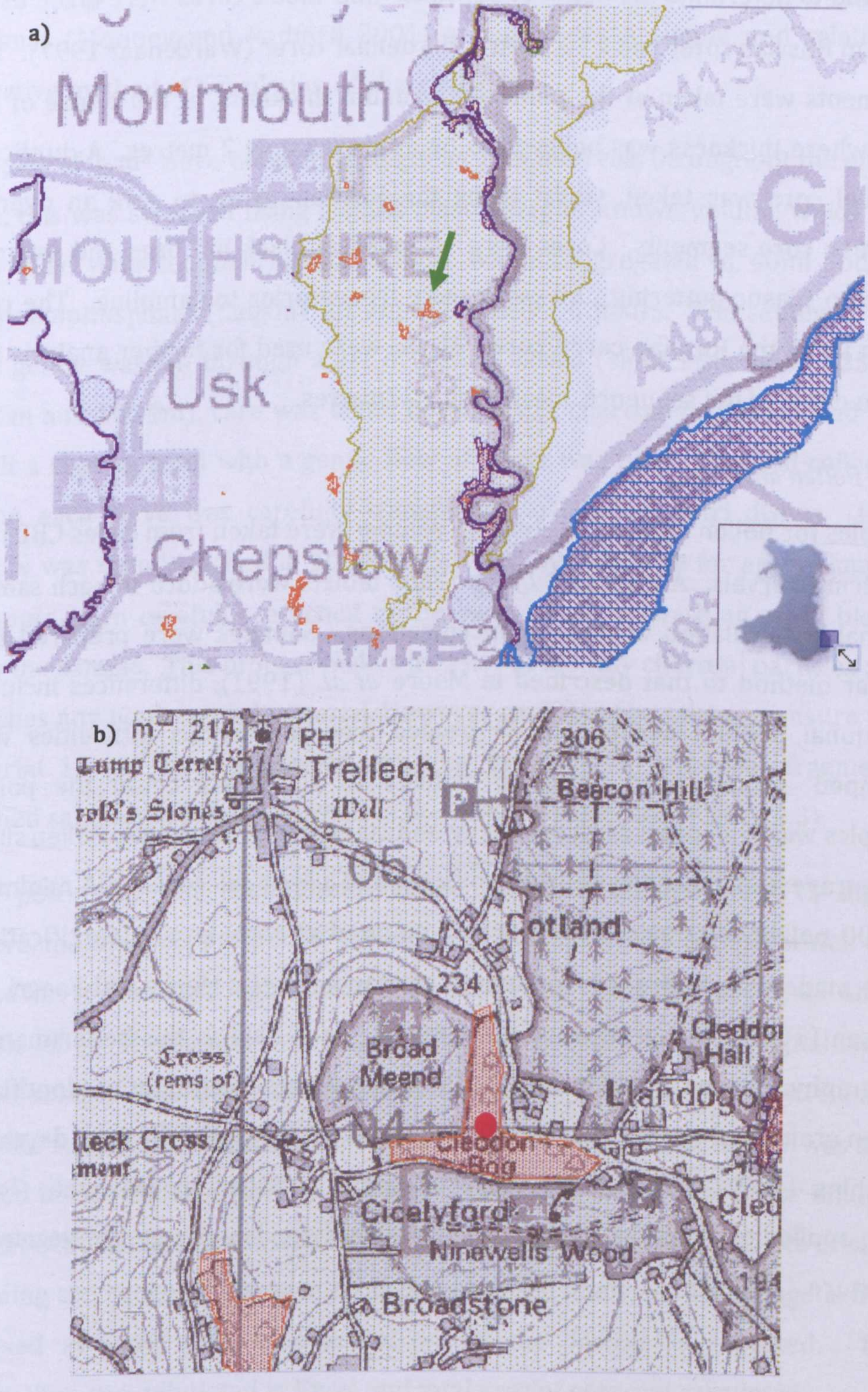


Figure 4.2: a) Location of the Cleddon Bog within the Wye Valley indicated by the green arrow,1:250,000 b) Location of Cleddon Bog within the Trellech-Wentwood Plateau, indicated by the shaded orange area at the centre of the map, coring site marked by red circle, 1:25,000. (Country Council for Wales 2011).



4.2 Methods

4.2.1 Coring technique

Transects of trial cores were used to establish the nature of the sediments of the bog and to determine the depth of deposits. One-metre cores were taken using a 10cm Russian corer and a 1.2 metre Wardenaar corer (Wardenaar 1997). The sediments were taken at the point of maximum thickness, at the centre of the bog, where thickness was believed to be approximately 2 metres. A duplicate parallel core was taken, whilst using the Russian corer, to give an overlap between core segments. Cores were wrapped in black bin bags and securely taped to plastic guttering. All cores were frozen prior to sampling. The core taken using the Russian corer, core $CBD_1\&_2$ were used for further analysis due to the depth of the sequence, measuring 1.27metres.

4.2.2 Pollen analysis

Samples for pollen analysis ca. 1cm^3 in volume were taken from cores CBD_1 & $_2$ at1-2cm intervals. A total of 3 *Lycopodium* tablets were added to each sample to enable calculation of pollen concentrations. Samples were prepared in a similar method to that described in Moore *et al.* (1991), differences included additional Sodium pyrophosphate treated due to previous difficulties with 'clumped' samples and therefore inability to accurately count the pollen. Samples were mounted in glycerol jelly and stained with Safranine. Pollen slides were traversed under the 400x magnification of a Meiji microscope. A minimum of 400 pollen of terrestrial plants was counted at each level. Identifications were made with reference to the keys of Moore *et al.* (1991) and Faegri and Iversen (1989), and to modern reference material held in the Department of Geography, University of Liverpool. The state of preservation of unidentifiable pollen grains and spores was classified in terms of: crumpled; broken; degraded (Cushing 1967). Counts were tabulated using an Excel spreadsheet. Zones were applied to the pollen diagram by eye, identifying key changes in vegetation structure.

4.2.3 Charcoal analysis

Charcoal analysis followed the photogrammetric method described in Mooney and Radford (2001) and Mooney and Black (2003). This particular methodology attempts to minimise processing so that charcoal breakage is minimal (Mooney and Radford 2001) and provides a simple and relatively objective method of calculation of charcoal area.

Samples of 1cm^3 were taken at contiguous 1cm intervals throughout the entire core, this was achieved using a small plastic plug of known volume which was then filled with sediment. Each sample was disaggregated in 40ml Sodium hexametaphosphate (Calgon) for approximately 24 hours. The sediment was then gently washed through a set of nested sieves (sieve sizes were 125μm, 250μm and 500μm), care was taken not to break charcoal fragments and as a result a shower head with a gentle flow of water was used. Material collected within each sieve was carefully transferred to labelled petri dishes. Each sample was then bleached in 10ml 6% Sodium hypochlorite for approximately 24 hours, then carefully returned to the sieve mesh for washing off of bleach from the sample. This process makes it easier to identify charcoal particles as it bleaches any non-charred material. However care must be taken to ensure that material is not over-processed, causing breakage of charcoal fragments. Washed samples are then returned to the labelled petri dish (Figure 4.3).

Each petri dish was then photographed using an Olympus X-9915 digital camera, mounted on a tripod at a distance of 20cm from the sample which was placed on a Medalight lightboard, with a ruler in the frame for scale and a sample label. The sample was retained for future reference. The digital image of the sample was then formatted using Adobe Photoshop CS3 v10.0 this involved re-sizing the image, then saving in 'tif' format. The 'tif' image was then opened in Scion Image (2009) and scale calibrated, then the area for analysis was selected using Scion Image software tools. Settings for analysis are created, including the range of pixels to be included in the analysis. The image is then analysed and the area of charcoal within the sample is reported. This information was tabulated in Excel and total area of charcoal calculated.

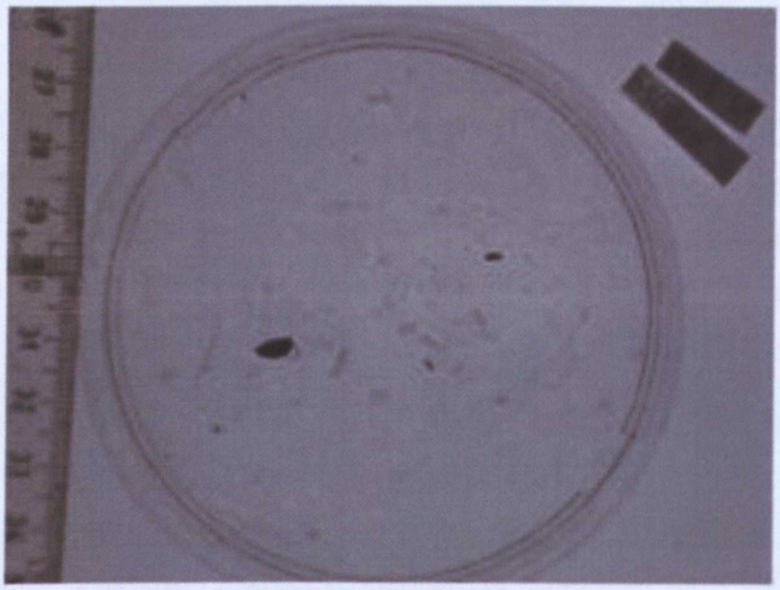


Figure 4.3: An example of a photograph of charcoal sample used to calculate area of charcoal in sample (photographed by C. Jones).

4.2.4 Chronology

Six 1cm^3 samples were taken from the peat cores at a range of depths chosen to cover the length of the core (core CBD$_1$&$_2$) and date significant events in the preliminary pollen diagram. These samples were sent for AMS radiocarbon dating of the humin fraction excluding potentially mobile fulvic and humic acids, at the NERC Radiocarbon Dating Facility (East Kilbride). Samples were digested in 2M Hydrochloric acid at 80°C for 8 hours, washed free from mineral acid with deionised water and then digested in 1M Potassium hydroxide at 80°C for 2 hours. The residue was rinsed free of alkali, digested in 2M Hydrochloric acid at 80°C for 5 hours, then rinsed free of acid, dried and homogenised. The total carbon was recovered as Carbon dioxide by heating with Copper oxide in a sealed quartz tube. The gas was converted to graphite by Iron/Zinc reduction. The graphite was then mounted on a pellet and the ^{14}C determined at the NERC AMS facility on a 5MV National Electrostatic Corporation AMS system. The initial run of six samples returned unreliable results from two levels and following investigations at the radiocarbon facility and review of methods used to obtain samples from the peat cores, it was proposed than an additional two samples would be analysed at similar depths to those thought to be unreliable

(Table 4.1). It was not possible to use the original depths as there was not enough material for dating.

Dates have been calibrated using Calib 510 (Stuiver and Reimer 1993). The age-depth model has been created using Psimpoll 4.10 (Bennett 1998), using linear regression (Figure 4.4).

Table 4.1: Radiocarbon dates for Cleddon Bog, U.K. Dates in **bold** are dates which are thought to be unreliable and therefore not included in age-depth curve.

Publication Code	Depth (cm)	Conventional Radiocarbon Age (yrs BP)	Calibrated Age (yrs BP)	Calibrated Result (2 Sigma, 95%) (yrs BP)
SUERC-27736	125-126	7060 +/-41	7892	7795 to 7965
SUERC-27737	103-104	6671 +/-38	7539	7476 to 7601
SUERC - 29498	96-97	6132 +/-38	7029	6912 to 7161
SUERC-27738	**90-91**	**n/a**		
SUERC-27739	**75-76**	**450 +/-40**		
SUERC-29497	63-64	3474 +/-36	3754	3641 to 3838
SUERC-27740	51-52	2131 +/-35	2113	1999 to 2177
SUERC-27741	28-29	520 +/- 37	537	504 to 632

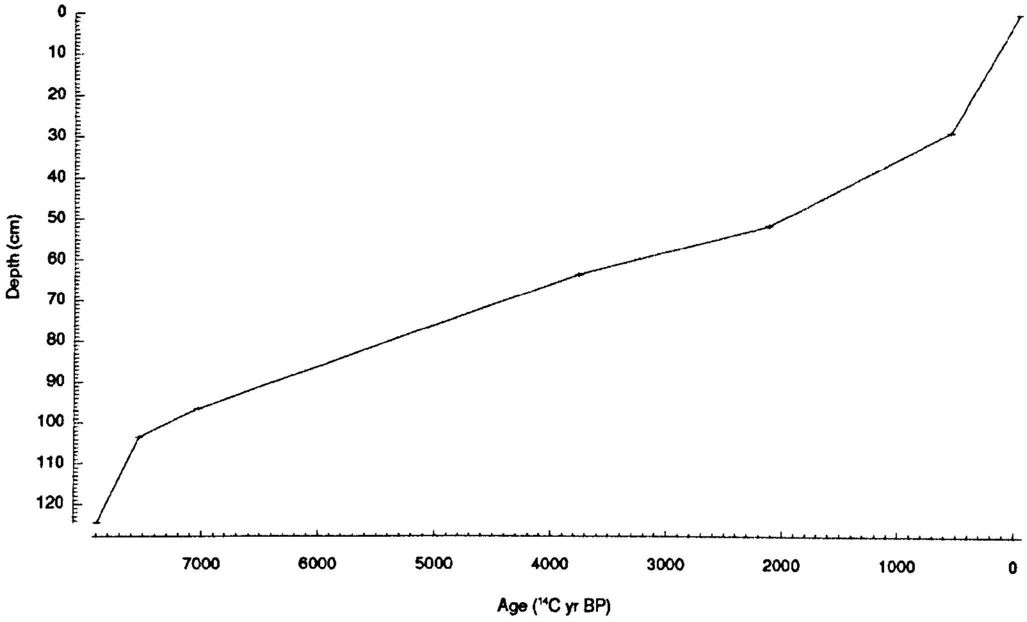


Figure 4.4: Linear age-depth model for Cleddon Bog, UK.

4.3 Results

The pollen diagram can be divided into four zones (Figures 4.5 & 4.6).

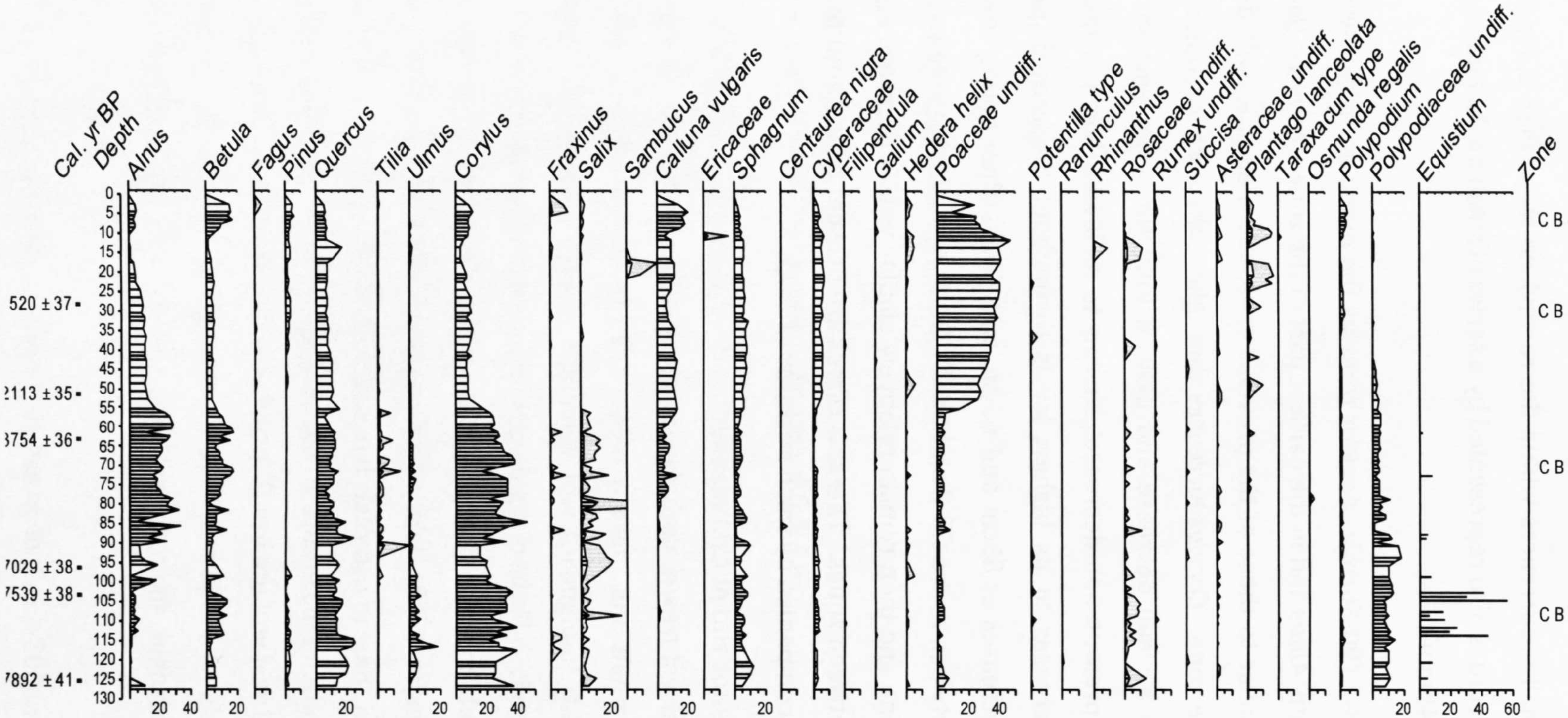
CB-1 (127-90cm): *Corylus* type and *Quercus* are the dominant taxa in this zone, with peaks of 45% and 30% respectively. These taxa reach their lowest levels in this zone towards the transition to zone CB-2. Also present are *Betula, Ulmus, Alnus* and *Pinus. Pinus* levels remain relatively low throughout the zone. *Ulmus* levels are at their highest of the record, showing a gradual decline towards the transition with zone CB-2. *Alnus* increases gradually towards the latter part of this zone, followed by a decrease similar to that of the other arboreal species at the zone transition. Both *Fraxinus* and *Salix* are present in small amounts throughout the zone. The first appearance of *Tilia* occurs in the latter section of the zone, where levels peak to 5% at 90cm. There are low levels of Poaceae and Cyperaceae, along with *Sphagnum. Polypodium* spore levels remain relatively constant throughout this zone and are at their highest throughout the record.

The charcoal record for this period sees a number of peaks in the >500μm record, one at 123cm, a series of peaks between 111cm and 103cm, 94cm and

92cm, all approximately 10mm^2. The 250-500μm record consists of a series of small occurrences within the record, no more than 2.39mm^2. The 125-250μm record is also represented by a series of small peaks amounting to no more than 0.45mm^2.

CB-2 (90-50cm): *Corylus* remains the dominant taxon within this zone, along with *Alnus* and in the earliest part of the zone, *Quercus*. *Quercus* peaks to levels similar to those of the previous zone, and then gradually decreases throughout the zone. *Corylus* increases throughout the early section on the zone, followed by a small decrease and plateau until the latter section of the zone, where representation decreases sharply to its lowest levels within the record. *Alnus* increases to its highest levels throughout the record, punctuated by sharp decreases at 85cm and 63cm, with levels then falling towards the transition between zones CB-2 and CB-3. *Betula* levels increase towards the middle of the zone and then remain relatively similar until a decrease again at the transition between zones. *Tilia* and *Ulmus* are present throughout this zone at low levels, accompanied by small amounts of *Salix*

Figure 4.5: Pollen diagram for Cleddon Bog, Wye Valley, UK., plotted versus depth. Exaggerated species indicated by the patterned curves and have been exaggerated by a factor of 5.



and *Fraxinus*. *Pinus* is hardly present within this section of the record. *Calluna vulgaris* is present at the start of this zone and values increase throughout, with levels of *Sphagnum*, Poaceae and Cypreaceae remaining constant. *Polypodium* decrease to approximately 10% and remains at this level through the zone.

This is the most notable zone in the charcoal record, with all size classes reaching their maximum values and most notable peaks at similar depths. The first of such peaks occurs between 79cm and 82.5cm, where the >500µm record peaks to 33.55mm^2, with levels decreasing at 81.5cm, only to increase and remain around 25mm^2. The 250-125µm record also peaks at 83.5cm, to 86.3mm^2, followed by a series of smaller peaks. A similar peak in charcoal particles between 125µm and 250µm occurs at 81.5cm. Both the 125-250µm and the 250-500µm records remain relatively low between 79.5cm and 65.5cm, when at 64.5cm there is another peak in each record, but this time to a lesser extent than the previous. The 500µm record peaks again at 68.5cm, to an area of 15.54mm^2. There are then a series of peaks at similar depths to those seen in other size class records, to levels similar to those seen in the early section of the zone, approximately 30mm^2. The 500µm record peaks to 18.64mm^2 at 57.5cm, and remains at a similar level for the following two to three centimetres. Both the smaller size class records remain low, although there is the presence of small amounts of charcoal <0.5mm^2.

CB-3 (50-10cm): Arboreal dominance within the record is overcome by a significant increase in *Poaceae* at the transition to CB-3 to approximately 25%, levels then continue to increase consistently throughout to almost 50%. *Tilia* is lost from the diagram completely. Levels of Cyperaceae are also at their highest throughout this zone. *Calluna vulgaris* and *Sphagnum* remain relatively constant throughout. *Alnus*, *Betula* and *Corylus* decrease throughout this zone, both *Alnus* and *Betula* decrease to zero at 10cm. *Quercus* remains relatively low throughout, with a sharp peak at 12cm to over 20%. *Pinus* levels increase throughout the zone and there is some representation of *Fagus*. *Plantago lanceolata* is present at 50cm, 28cm and 20cm. *Plantago* levels decrease to zero and remain around zero throughout the zone.

Charcoal area within all size classes in this zone are low, with just to small peaks occurring in the >500μm record and 250-500μm record. However in the latter section of the record the 125-250μm record peaks at 15.5cm, with an area of 8.15mm^2. This part of the zone also sees a series of smaller peaks, < 0.5mm^2, in both the >500μm and250-500μm size classes.

CB-4 (10cm-2.5cm): This final zone sees an increase in arboreal pollen along with a consistent representation of heathland species. *Alnus, Betula, Corylus, Pinus* increase significantly to values similar to earlier sections of the record. *Quercus* levels decrease from previous peak in zone CB-3, and then remain relatively constant throughout. The highest levels of *Calluna vulgaris* in the record are present within this zone, >20%. Poaceae decreases significantly throughout the zone, accompanied by decreasing levels of *Sphagnum* and Cyperaceae. *Plantago lanceolata* is also present throughout the zone, along with low levels of *Polypodium*.

The charcoal record for the final zone sees a peak in charcoal area in the 125-250μm record, to 10.28mm^2 at 2.5cm. There is also a peak in the >500m record at a similar depth, 2.5cm and 3.5cm, with a charcoal area of 4.31mm^2 and 5.67mm^2 respectively.

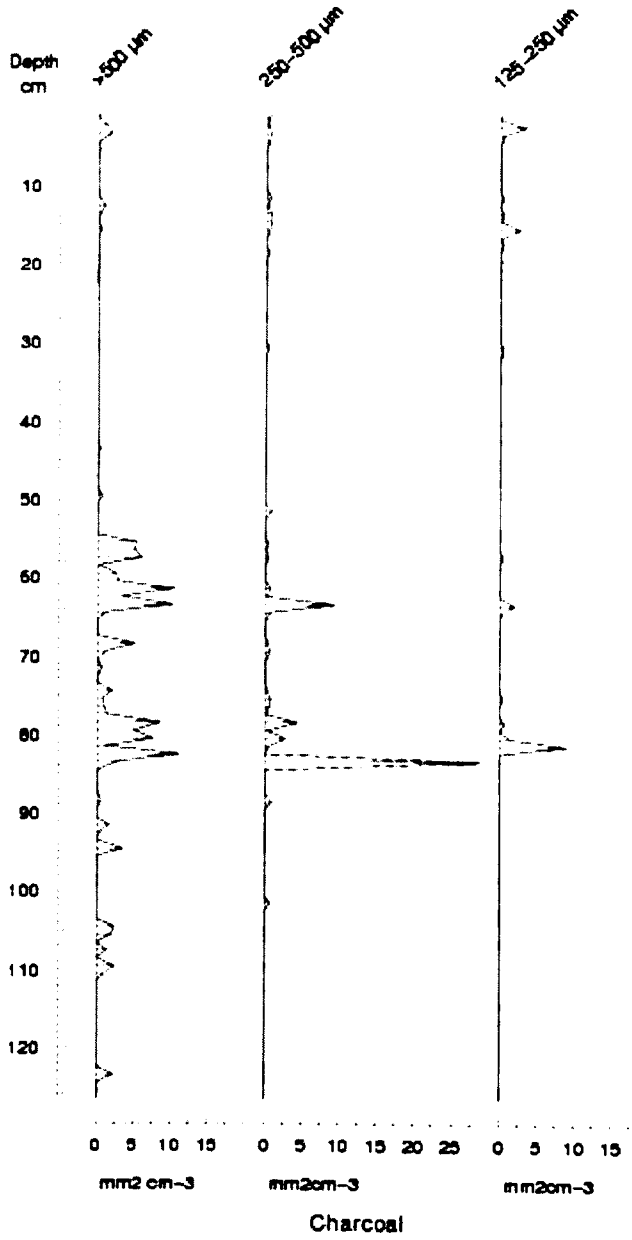


Figure 4.6: Charcoal record for Cleddon Bog including >500µm, 250-125µm and 125-250µm record, plotted against depth.

4.4 Discussion

CB1 (7900-6400 cal yrs BP) (Figures 4.7 & 4.8):

The dominance of trees and shrubs during this period suggests that the area is composed of a relatively intact woodland. Species within the woodland include *Quercus*, *Corylus*, *Betula* and *Ulmus*. There are also large amounts of *Polypodium* which is an epiphytic fern, tending to grow on *Quercus* again implying the presence of a local woodland. Non-arboreal species are present in small amounts, also supporting the presence of a wooded community. This would suggest that sample site conditions are likely to be under relatively closed-canopy conditions and so a majority of the pollen deposited is from the local vegetation. However there are large amounts of *Sphagnum* present which may suggest that the local, underlying ground conditions were relatively moist or that there were small patches of open land, that could have been colonised by bog species (*Sphagnum*, Cyperaceae) and grassland species (Poaceae) and Rosaceae sp..

There is some evidence of local burning of the landscape due to the presence of >500µm charcoal fragments. Amounts do not appear to be significant, however there is a slight increase towards the end of the zone linked with a slight decrease in woody species, and *Polypodium* together with an increase into *Calluna vulgaris*, leading into zone CB2.

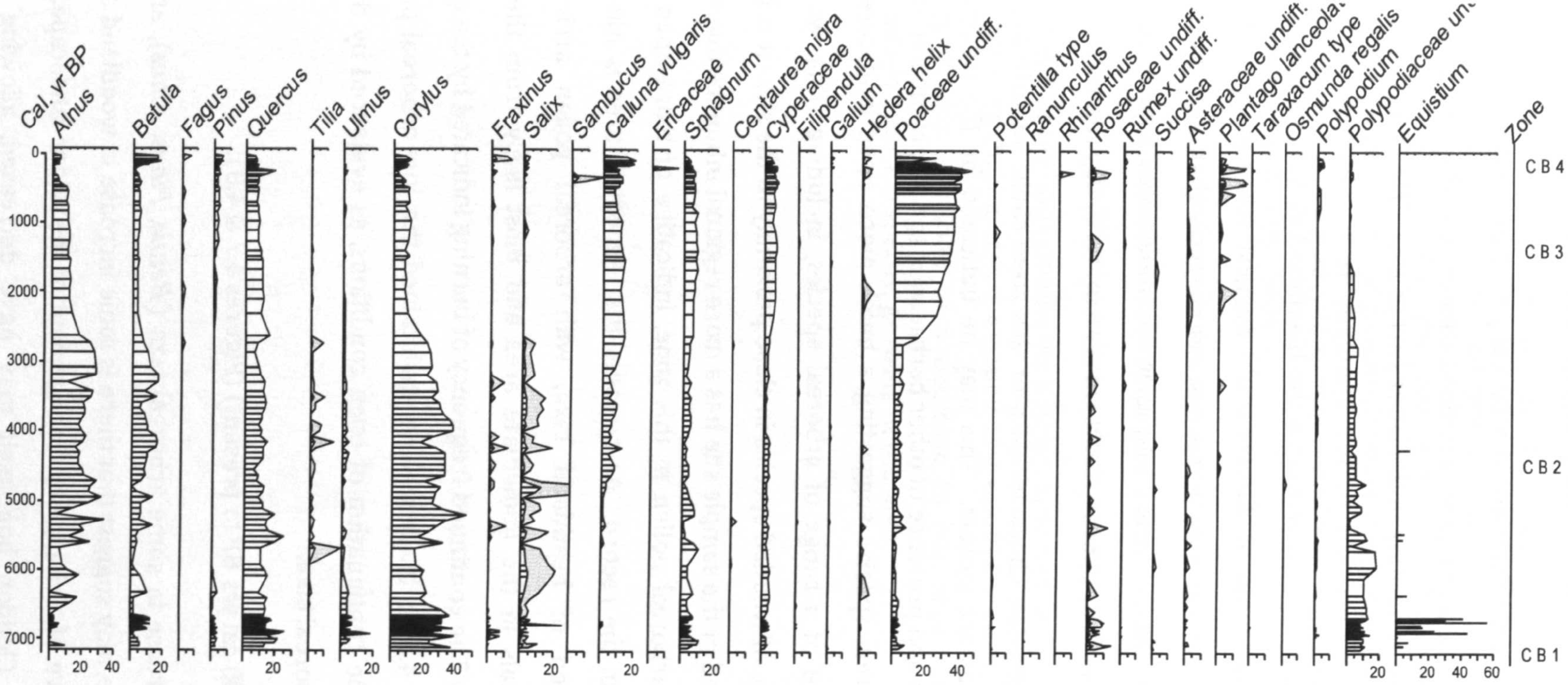
CB2 (6400-2500 cal yrs BP) (Figures 4.7 & 4.8):

Conditions appear similar to that of the previous zone, with woodland dominating the landscape. Again resulting in the likelihood that pollen deposited at the sample site was from local vegetation. However in this instance, the woodland is more diverse than the previous *Quercus*/*Corylus* woodland of zone CB1. *Corylus* is still the dominant species, with *Alnus* and *Quercus* present in large amounts. *Ulmus* and *Betula* are also present in small amounts. Small amounts of *Tilia* are also present in this zone, however due to the low pollen producing nature of *Tilia*, the increase *Tilia* pollen in the diagram is significant. The presence and increase in *Alnus* in this zone may suggest that ground conditions were wetter than previously this too is seen at other sites in southern Wales, a significant rise in *Alnus* approximately 7000yrs BP (Chambers 1983). This may be supported by the increasing presence of *Calluna vulgaris* and continued presence of *Sphagnum*, potential increase in bog species. This could be an indication of the presence of open, heathland areas near to the sample site.

During this zone there is evidence of a decline in *Tilia*, coinciding with the many recorded declines across lowland Britain (Grant *et al.*. 2010). Grant (*et al.*. 2010) discuss the potential causes of *Tilia* declines in Britain and correlation between aspects discussed in their paper and the pollen stratigraphy and site characteristics of Cleddon bog, two potential causes can be postulated, paludifaction and anthropogenic activity. Paludification at this site would be related to the increase in surface / soil wetness, potentially leading to mire conditions. This is indicated at the first notable decline in *Tilia*, with the subsequent increase in *Calluna vulgaris* pollen recorded at the site, supporting the potential for paludification as a cause for the loss of *Tilia* at the site. However *Tilia* has a continued presence in the larger area, with values >5%, suggesting the first decline is local. The further decline in *Tilia* in the pollen record also occurs as there is a notable decline in *Ulmus* potentially indicative of anthropogenic activity in the area as a cause (Grant *et al.* 2010). The combined decline of *Tilia* and *Ulmus*, with a slight increase in *Corylus*, could suggest a removal or thinning of the woodland canopy resulting in an increase of flowering understorey taxa (Grant *et al.* 2010).

The charcoal record indicates that there is a significant amount of burning in the area, with two main phases. The earliest phase (~82cm / ~6200yrs BP) may correlate with a slight decrease in woodland species at the early part of the zone, which also correlates with the onset of an increase in *Calluna vulgaris*. The second phase is also likely to be local burning with high values of >500µm charcoal, this is again consistent with a decrease in arboreal pollen and a continued strengthening of the influence of heathland and herbabceaous species. It is possible to interpret that this phase of burning may have had a significant effect upon the wooded landscape and may have been the instigating factor in the opening of the bog. The final significant phase of macrocharcoal deposits, at approximately 65cm / 4000 yrs BP coincides with a marked increase in bog species, in particular *Calluna vulgaria*. This phase of burning sees the onset of relatively high proportions of *Calluna vulgaris*, than has been seen in the previous zone, suggesting that this phase of buring within the landscape is likely to have played a part in the changing of vegetation from mainly to arboreal, to open, bog conditions. Pollen from arboreal taxa can also be seen to decline significantly, most likely as a result of an increased frequency of burning within the landscape, therefore providing opportunity for vegetation change.

Figure 4.7: Pollen diagram for Cleddon Bog, Wye Valley, UK., plotted versus calendar years BP. Exaggerated species indicated by the patterned curves and have been exaggerated by a factor of 5.



CB3 (2500-200 cal yrs BP) (Figures 4.7 & 4.8):

The significant decrease in arboreal pollen and increase in non-arboreal pollen may indicate significant woodland clearance in the area, potentially linked with the phase of burning in the latter part of zone CB2. This is also supported by the significant decrease of the epiphytic fern, *Polypodium*. The presence of *Plantago lanceolata* indicates the likelihood of human activity in the area, and limited amounts of *Rumex* could suggest some grazing taking place in the vicinity. An increase in *Cyperaceae* suggests that local ground conditions are getting wetter or remaining relatively moist, also supported by the continued presence of bog species *Calluna vulgaris* and *Sphagnum*.

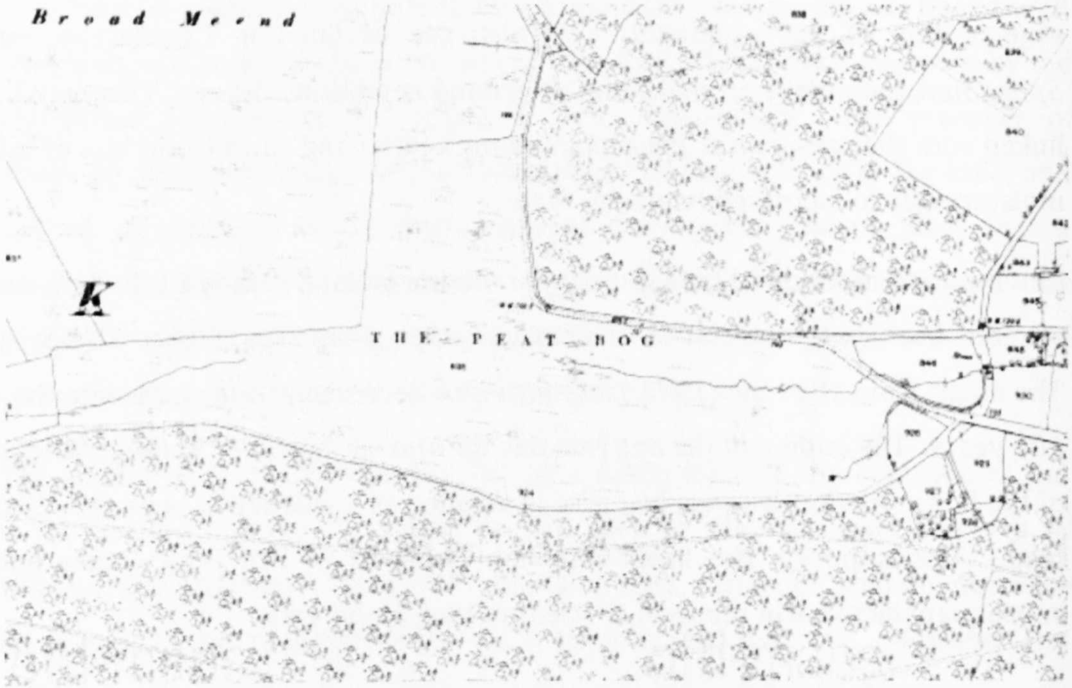
The vegetation characteristics of this zone could indicate the initiation of the wood pasture system. This may be indicated by the significant increase in Poaceae and presence of other herbaceous species, combined with the decrease in arboreal species suggesting a much more open landscape. However the presence of a range of arboreal species, including *Tilia*, would support the presence of wooded species in close proximity to the site. It is likely that pollen deposited at the sample site has a more regional influence due to the dominance of non-arboreal pollen in this zone, indicative of more open conditions than earlier in the record. As a result, the immediate area is likely to have been composed of heathland taxa, with arboreal pollen arriving from some individuals in the immediate area and most likely from the wider Trellech plateau. The continued frequency of burning indicated by the charcoal diagram (Figure 4.8) is likely to have maintained the low arboreal pollen values and aided the continuation of open conditions, as evidenced by the proportion of non-arboreal taxa.

CB4 (200 cal yrs BP to present) (Figures 4.7 & 4.8):

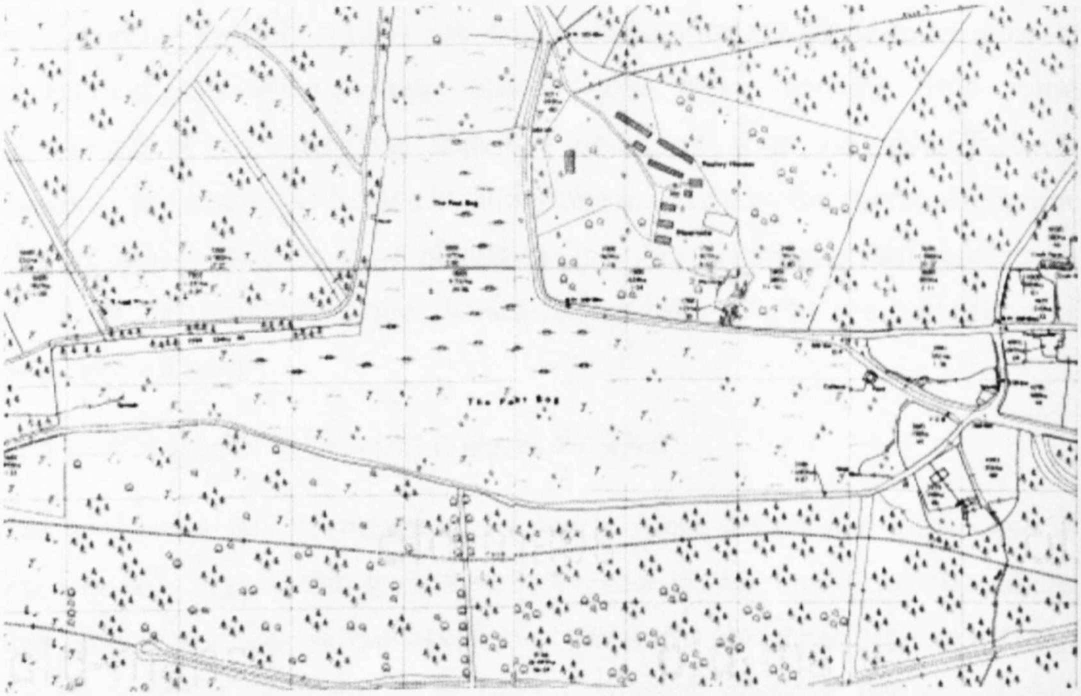
The increase in some arboreal taxa (*Betula*, *Pinus*, *Alnus*), and a decrease in *Poaceae*, may suggest that there is some increase in woodland areas, potentially indicative of a change in management of the wider landscape. Human activity on the Cleddon bog itself may have decreased, allowing the subsequent encroachment of woodland species that can be seen at present and also increase in arboreal species in the pollen diagram. This is likely to be as a result of lack of grazing of the wood pasture and therefore decrease in control of regeneration of the woodland. We also see declines in Cyperaceae and *Sphagnum*, potentially an indication of ground conditions drying. This may be linked with the presence of *Pinus* plantations nearby and subsequent loss of soil moisture due to increased intake by *Pinus*.

The increase in arboreal taxa growing in the immediate vicinity of the bog can also be observed by correlation of historical maps of the area (Figure 4.8 a & b). The maps, from 1881 and 1972, clearly show a decrease in bog size in less than 100 years. The outline of the bog remains the similar, however to the northeast of the bog a previously open, bog area is mapped as a wooded area on the 1972 map. This supports the likelihood of a decrease in bog area / taxa and subsequent increase in arboreal species growing in the area.

Figure 4.8: a) Image of historical map of the Cleddon Bog area from 1881 original 1:2500 scale map. (Sourced from Old-maps.co.uk, 2011).



b) Image of historical map of the Cleddon Bog area from 1972, original 1:2500 scale map. (Sourced from Old-maps.co.uk, 2011).



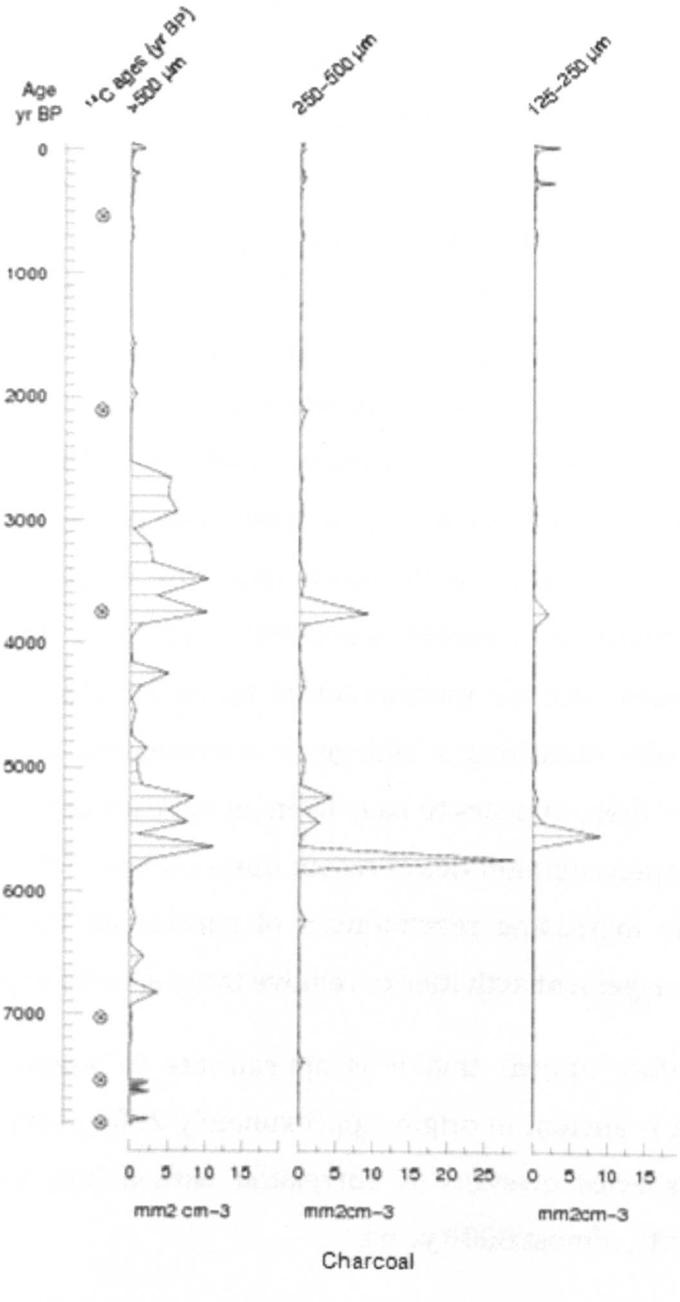


Figure 4.9: Charcoal record for Cleddon Bog, UK, including >500µm, 250-500µm and 125-250µm record, plotted against years before present.

Palaeoecological analysis appears to indicate that there has been a woodland community present at this site at least 8000 years ago. This woodland community has changed in species composition and structure within the landscape over this period. Initially the woodland was dominated by *Quercus* and *Corylus* and the site was likely to be under a closed canopy due to the dominance of arboreal species. However by 7000 years ago the species composition had become more diverse with arboreal species such as *Tilia* and *Alnus* representing increasing proportions of the pollen preserved at the site. Approximately 2000 years ago species vegetation structure changed significantly, with a significant increase in arboreal species and an increase in herbaceous species, namely Poaceae, Cyperaceae, and heathland taxa *Calluna vulgaris* and *Sphagnum*. This period is envisaged to be the onset of the wood pasture system, an open community with a scattering of trees, similar to the findings of Brown (2010) in the Wentwood. Brown (2010) also noted a decrease in arboreal pollen approximately 2000 years BP and an increase in non-arboreal pollen at that time. This is likely to be related to the Iron Age and Romano-British clearances, with continuous low levels of woodland and agricultural activity until recent woodland expansion. The nature of this opening correlates with the termination of burning indicated by the charcoal record, potentially indicating a change in management of the landscape. In recent centuries there appears to have been an increase in arboreal species and a loss of some open communities. Present observations of the bog also support this due to the increasing regeneration of species on the bog surface and subsequent management activities to remove these species to preserve the bog.

It would therefore appear that it is appropriate to suggest that the wood pasture system is ancient in origin, approximately 2000 years ago and that the present local species diversity is correlated with a long continuity of tree species at this site, almost 8000 years.

4.5 Conclusions

In conclusion, there has been a continued presence of wooded species at Cleddon Bog, although the dominance of woodland at the site has changed throughout the mid-to late-Holocene. Fire events have been recorded by the charcoal record and appears to relate to the increase in heathland species, *Calluna vulgaris*, this relationship is further explored in the subsequent chapter. Although the significant decrease in burning approximately 2500 years BP does appear to lead in a decrease in arboreal species and an increase in non-arboreal species, associated with the development of the wood-pasture system, it is entirely likely that the high local species diversity of the bog at present is due to the continuity of woodland at the site. A continuation of the investigation of the relationship between burning within the landscape of the British Isles and vegetation is continued in Chapter 5, with the analysis of numerous charcoal records together with the pollen record.

4.6 References

Adobe photoshop CS3, San Jose, California.

Bennett, K.D. (1998) Psimpoll 4.10 and Pscomb 1.03 - C programs for plotting pollen diagrams and analysing pollen data. http//www.kv.geo.uu.se/psimpoll_manual/4.00/psimpoll.html

Bergmeier, E., Petermann, J., Schröder, E. (2010) Geobotanical survey of wood-pasture habitats in Europe: diversity, threats and conservation, *Biodiversity and Conservation,* DOI 10.17007/s10531-010-9872-3.

Biodiversity Action Plan UK (1995) *Biodiversity: the UK action plan.* HMSO, London.

Bradshaw, R.H.W., Hannon, G.E., Lister, A.M. (2003) A long-term perspective on ungulate-vegetation interactions, *Forest Ecology and Management,* **181**, 267-280.

Brown, A.D. (2010) Pollen analysis and planted ancient woodland restoration strategies: a case study from the Wentwood, southeast Wales, UK. *Vegetation History and Archaeobotany,* **19**, 79-90.

Chambers, F.M. (1983) Three Radiocarbon-Dated Pollen Diagrams from Upland Peats North-West of Merthyr Tydfil, South Wales, *Journal of Ecology,* **71**, 2, 475-487

Country Council for Wales, http://www.ccw.gov.uk, accessed March 2011.

Cushing, E.J. (1967) Evidence for differential pollen preservation in late Quaternary sediments in Minesota, *Review of Palaeobotany and Palynology,* **4**, 87-101.

Desender K, Ervynck A, Tack G (1999) Beetle diversity and historical ecology of woodlands in Flanders. *Belgian Journal of Zoology,* **129**,139–156.

Faegri, K., Iversen, J., Kaland, P.E., Krzywinski, K. (1989) *Textbook of pollen analysis,* Wiley, Chinchester.

Grant, M. J., Waller, M. P., Groves, J.A. (2010) The *Tilia* decline: vegetation change in lowland Britain during the mid and late Holocene, *Quaternary Science Reviews*, 1-15.

Grimm, E.C. (1991) *TILIA* and *TILIA GRAPH*, Illinois State Museum, Springfield.

Labaune C, Magnin F (2002) Pastoral management vs. land abandonment in Mediterranean uplands: impact

on land snail communities, *Global Ecology and Biogeography*, 11, 237–245.

Mitchell, F.J.G. (2005) How open were European primeval forests? Hypothesis testing using palaeoecological data, *Journal of Ecology*, **93**, 168-177.

Mooney, S., Black, M. (2003) A simple and fast method for calculating the area of macroscopic charcoal isolated from sediments, *Quaternary Australasia*, **21**, 1, 18-21.

Mooney, S., Radford, K. (2001) A simple and fast method for the quantification of macroscopic charcoal in sediments, *quaternary Australasia*, **19**, 1, 43-46.

Moore, P.D., Webb, J.A., Collinson, M.E. (1991) *Pollen Analysis*, Blackwell Scientific Publications, Oxford.

Mosquera-Losada, M.R., McAdam, J.H., Romero-Franco, R. (2009) Definitions and components of agroforestry practices in Europe. In: Riguerio-Rodriguez, A., Mc Adam, J., Mosquera-Losada, M.R. (eds) Agroforestry i Europe. Current status and future prospects. Springer, Berlin, 3-19.

Müller J, Bußler H, Bense U et al. (2005) Urwald relict species. Saproxylic beetles indicating structural qualities and habitat tradition, Urwaldrelikt-Arten : xylobionte Ka¨fer als Indikatoren fu¨r Strukturqualitat und Habitattradition. Waldo¨kologie online 2:106–113. (http://www.afsv.de/download/literatur/waldoekologie-online/waldoekologie-online_heft-2-9.pdf) Accessed July 2010.

Old-maps.co.uk, http://www.old-maps.co.uk, accessed March 2011

Peterken, G.F. (2008) *Wye Valley.* Harper Collins. London.

Peterken, G.F. (ed.) (2007) *Woodlands of the Lower Wye Valley: Origins, History and management,* Wye Valley AONB Unit, Monmouth.

Pryor, S.N., Smith, S. (2002) *The area and composition of plantation on ancient woodland sites.* The Woodland Trust (www.woodland-trust.org.uk/policy/publicationsindex.htm).

Scion Image, available at www.sciocorp.com. (accessed January 2009)

Sumner, G. (1997) Wales. In: Wheeler, D., Mayes, J. (eds) *Regional climates of the British Isles.* Routledge, London, 131-157.

Surrey Biodiversity Partnership—Wood Pasture and Parkland working group (2008) Revised definition for wood-pastures. (http://www.surreybiodiversitypartnership.org/xwiki/bin/download/WoodPastureParkland/ActionPlan/Revised%20definition%20for%20wood%20pasture.doc) Accessed July 2010.

Stuiver, M., Reimer, P. (1993) Extended ^{14}C database and revised CALIB radiocarbon calibration program, *Radiocarbon,* **35**, 215-230.

Taboada A, Kotze DJ, Ta´rrega R et al. (2006) Traditional forest management: do carabid beetles respond to human-created vegetation structures in an oak mosaic landscape? *Forest Ecology and Manage*ment, **237**, 436–449.

Tucker GM, Evans MI (1997) *Habitats for birds in Europe. A conservation strategy for the wider environment. BirdLife International,* Cambridge.

Vera FW (2000) Grazing ecology and forest history. CABI, Wallingford.

Wardenaar, E.C.P. (1987) A new hand tool for cutting peat profiles. *Canadian Journal of Botany,* **65**, 1772-1773.

Wimpenny, J. (ed.) (2000) *Trellech 2000: an account of the life in Trellech and Catbrook at the start of the New Millennium.* Bioline, Cardiff.

Wye Valley Area of Outstanding Natural Beauty (AONB) Management Plan 2009-2014, published March 2010, (http://www.wyevalleyaonb.org.uk/pages/who_and_how/management_plan.asp) accessed July 2010.

Chapter 5

Fire regimes in the British Isles during the Holocene

5.1 Introduction

Fire is an important disturbance mechanism in the Earth system, affecting ecosytems and the global carbon cycle (Marlon *et al* 2008). It has been present in the geological record since the appearance of terrestrial plants (Bowman *et al* 2009) and some eight billion tonnes of vegetation are burned each year by natural wildfires (Scott *et al* 2000). Our knowledge of past fire regimes is key to understanding the relationship between burning, climatic change, vegetation patterns and anthropogenic activities. Attempts have been made to model fire regimes, incorporating fuel load, climate and human influence on ignition (Thonicke *et al* 2005), however the effect of additional factors such as fuel type may be important to improve the predictive value of fire models, Glob-FIRM incorporated into the LPJ-DGVM (Thonicke *et al* 2005, Thonicke *et al* 2001); Sheffield DGVM (Woodward *et al* 2001); IBIS (Foley *et al* 1996). Burning has impacts on vegetation structure and the dynamics and these interactions have been studied at present in the Swedish Boreal forest, where depth of burn was found to be more important in changes in understory vegetation structure, rather than fire front intensity (Schimmel and Granstrom 1996). In the North American Boreal zone vegetation composition has significant effects upon the fire regime (Lynch *et al* 2001), however weather conditions (precipitation) were also noted as having significant impacts on fire regime (Larsen and

MacDonald 1995). The effect of fire within the alpine ecosystems has also been investigated, for example southern Switzerland (Delarze *et al* 1992), where recovery after fire by both herbaceous and woody species is rapid, however with increased fire frequency, diversity decreases and soil conditions deteriorate. Past fire-vegetation interactions have been investigated using pollen-charcoal relationships in the boreal ecosystems, Carcaillet *et al* (2001) concluded that the Canadian boreal fire regime has largely been influenced by the change in vegetation structure and connectivity, as a result in changes driven by climate change. The temperate ecosystem, for example, Whitlock *et al* 2003, investigated a number of sites in northwestern USA, revealing that climatic conditions determined vegetation structure, which in turn affected the fire regime. Wildfires in the Alpine ecosystem are rare and mainly linked to anthropogenic activity, effects on vegetation generally lead to the suppression of fire-sensitive taxa (*Ulmus, Tilia, Hedera, Fagus*) (Tinner *et al* 2000; Tinner *et al* 2005). The Mediterranean regions also reveal relationships between fire frequency and the suppression of fire sensitive taxa (*Abies alba, Quercus ilex*) resulting in a decrease in diversity of arboreal species and the establishment of the present fire-adapted vegetation type (Colombaroli *et al* 2007).

Fire in the British Isles has been investigated using small regional studies, particularly in Scotland, (Simmons and Innes 1988, Edwards *et al* 2000, Shaw and Tipping 2006). Moore (2000) addressed the question of forest fire and human interaction in the early Holocene woodlands of Britain. The temperate, deciduous nature of the majority of British woodlands raises questions about the potential for naturally ignited fires, due to the low flammability of species with almost all fires thought to be of anthropogenic origin (Bennett *et al* 1990b; Rackham 1986). Consequently the role of fire as a disturbance mechanism in temperate forest is not generally recognized (Peterken 1993). This paper addresses the questions of the role of fire in the British Isles during the Holocene and the balance between natural and anthropogenic ignition, by using charcoal records and associated pollen data from across the British Isles.

Charcoal fragments have been widely used as an indicator of fire in the palaeoecological record at several temporal and spatial scales (Power *et al* 2008). A variety of sites have been used to collect these records: lakes, small forest hollows, peat bogs and soil profiles. This study restricts itself to records obtained from lakes and peat bogs. Lake records of burning have been used successfully to investigate fire and fuel relationships (Marlon *et al* 2006) and vegetation interactions with fire regimes (Delarze *et al* 1992, Tinner *et al* 2005).

The dataset used comprises of 57 charcoal records from lakes and bogs across the British Isles (Fig. 1; Table 1). The varying nature in methods used to record these data require a standardisation of the dataset. I also aim to investigate the relationship between burning and plant taxa. This interaction has been investigated using pollen data collected from 46 of the charcoal records in the British Isles Charcoal Database (BICD).

5.2 Methods

5.2.1 Data

An extensive literature search for charcoal records in the British Isles was performed, resulting in the collection of some 57 records from different sites (Fig 5.1; Table 5.1). Many of these records were accompanied by either a pollen or plant macrofossil record. Charcoal data were collected from published literature. Data were extracted from the literature by digitising the original published figures, using the program 'Data Digitiser'. The points plotted on the original figures were then used to create a table of charcoal values by depth.

As a consequence of using published data spanning over two decades, consistent calibration and age models were required for each site. Almost 400 uncalibrated radiocarbon dates were entered into the database. The radiocarbon dates were calibrated using Calib v.5.0 (Stuiver *et al.*, 1993) and errors assigned to each age. All 57 sites had two or more radiocarbon dates, with the exception of Tory Hill Basin (O'Connell *et al.*, 1999), for which the published varve chronology was used. When the surface sample of the sedimentary core was identified as being modern the year of sampling was assigned as the surface sample age, for example; a figure published in 2003 would have a surface sample age of -53yr B.P. Ages were expressed as years before present (BP) where the present was defined as AD 1950. Age-depth models were then created using Psimpoll (Bennett, 1998) and the simplest model was selected.

As a result of the varying methods of collection and analysis, charcoal values collected were expressed in a number of ways (influx, charcoal : pollen, concentration, etc). This difference makes it difficult to compare sites with differing methods, consequently the data were standardised. The standardisation process involved the identification of the maximum charcoal value in a site record; all charcoal values in that site record were then divided by this maximum charcoal value, therefore leaving a record ranging from '0' to '1', '1' being the maximum charcoal value and '0' reflecting the absence of charcoal at that depth.

Pollen data for 14 pollen types was digitised from sites with accompanying pollen records (*Alnus, Betula, Corylus, Fraxinus, Pinus, Quercus, Salix, Tilia, Ulmus, Calluna,* Cyperaceae, *Plantago lanceolata,* Poaceae, *Rumex*). The pollen types chosen for analysis were the major trees, shrubs and herbs selected for their abundance, known fire ecology or relationships to cultural activity (Bradshaw *et al* 2010).

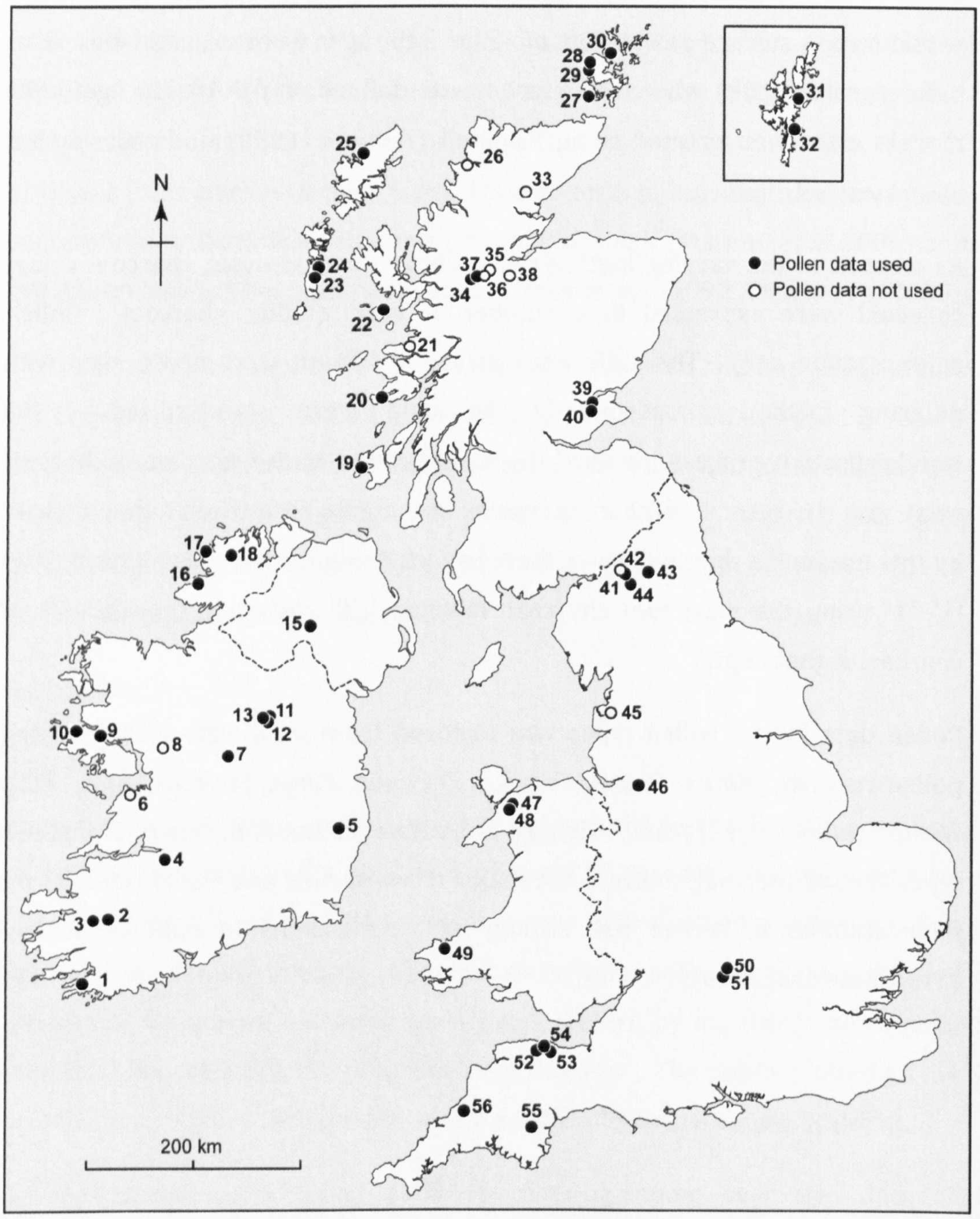


Figure 5.1: Location of study sites included in British Isles Charcoal Database (BICD). Sites included in CANOCO analysis (filled circles), sites only included in temporal analysis (hollow circles).

Table 5.1: Sites included in British Isles Charcoal Database (BICD). Charcoal method column indicates charcoal method used by analyst; SIEV: Sieved, POLS: Pollen Slide, POLS(pc): point count method, SIPO: Sieved and pollen slide, NOTK: Not known.

Site name	Site No.	Publ. No.	Latitude	Longitude	Charcoal method	No. of Radiocarbon dates	Altitude (metres a.s.l)	Publication
Ireland:								
Mount Gabriel	1	43	51°33'38"N	9°32'34"W	NOTK	6	150	*Mighall et all 2008*
Derrycunihy Wood	2	15	52°01'N	9°25'W	POLS	4	17	*Mitchell 1988*
Camillan Wood	3	15	52°02'N	9°34'W	POLS	3	17	*Mitchell 1988*
Tory Hill Basin	4	12	52°32'N	08°41'W	SIEV	Varve	30	*O'Connell et al 1999*
Kelly's Lough	5	34	52 57'17"N	06 25' 45"W	POLS (pc)	9	585	*Leira et al 2006*
Lios Lairthín Mór ringfort, Burren	6	3	53°5'N	9°13'W	SIEV	10	270	*Jeličić&O'Connell 1992*
Mongan Bog	7	21	53°19'48"N	7°55'48"W	SIEV	13	45	*Barber et al 2003*
Abbeyknockmoy Bog	8	21	53°26'27"N	08°46'3"W	SIEV	10	60	*Barber et al 2003*
Lough Maumeen	9	6	53°29'N	9°39'W	SIEV	7	250	*Huang 2002*
Lough Sheeauns	10	5	53°33'N	10°01W	NOTK	13	<160	*Molloy&O'Connell 1991*
Derragh Bog	11	45	53°45'49"N	7°24'7"W	NOTK	12	70.5	*Brown et al 2005*
Derragh Lough	12	45	53°45'59"N	7°24'25"W	NOTK	4	62	*Brown et al 2005*
Balywillin Crannog	13	45	53°47'1"N	7°24'46"W	NOTK	7	62	*Brown et al 2005*
Killymaddy Lough	14	46	54°32'N	06°46'W	POLS	4	100	*Hirons&Edwards 1986*
Lough Catherine	15	46	54°36'N	07°25'W	POLS	4	60	*Hirons&Edwards 1986*
Lough Mulleghlahan	16	1	54°46'34.07"N	8°28'4.12"W	POLS (pc)	6	40	*Fossit, J.A.1994*
Altar Lough	17	1	55°01'N	08°24'W	POLS (pc)	5	30	*Fossit, J.A.1994*
Lough Nabraddan	18	1	55°01'N	08°1'W	POLS (pc)	5	20	*Fossit, J.A.1994*
Scotland:								
Loch a'Bhogaidh	19	18	55°43'30"N	6°24'12"W	POLS	6	65	*Edwards&Berridge 1994*
Loch an t'Suidhe	20	2	56°18'10"N	6°14'27"W	POLS	5	<85	*Edwards et al 2007*
Kentra Moss	21	23	56°45'N	05°50'W	SIEV	6	10	*Ellis&Tallis 2000*
Kinloch	22	49	57°0'56"N	6°17'4"W	POLS	5	11	*Hirons&Edwards 1990*
Loch Lang	23	17	57°14'40"N	7°17'48"W	POLS (pc)	6	80	*Bennett et al 1990a*
Loch a'Phuinnd	24	4	57°22'N	7°16'W	POLS	5	10	*Fossit 1996*
Loch Buailaval Beag	25	4	58°16'N	6°46'W	POLS	5	50	*Fossit 1996*
Lochan na h-Inghinn	26	20	58°15'15"N	5°05'30"W	SIPO	6	65	*Froyd 2006*
Loch of Torness	27	31	58°46'44"N	3°17'31"W	POLS(pc)	5	15	*Bunting 1996*
Quoyloo Meadow	28	14	59°4'4"N	3°19'9"W	POLS (pc)	5	33	*Bunting 1994*
Crudale Meadow	29	14	59°1'46"N	3°18'50"W	POLS (pc)	5	9	*Bunting 1994*
Loch of Knitchen	30	31	59°8'23"N	3°0'1"W	POLS(pc)	5	158	*Bunting 1996*
Dallican Water	31	16	60°23'30"N	1°06'W	POLS	6	56	*Bennett et al 1992*
Loch of Clickimin	32	33	60° 9'3.84"N	1° 9'54.99"W	NOTK	6	1	*Edwards et al 2005*
Reidh-lochan	33	20	58°02'13"N	4°07'26"W	SIPO	6	160	*Froyd 2006*
NHP	34	9	57°15'21"N	5° 1'5"W	POLS	2	NOTK	*Shaw&Tipping2006*
Loch an Amair	35	20	57°17'20"N	4°53'25"W	SIPO	7	315	*Froyd 2006*
BEAT	36	9	57°15'29"N	4°58'0"W	POLS	3	NOTK	*Shaw&Tipping2006*
PB	37	9	57°15'39"N	4°59'17"W	POLS	2	NOTK	*Shaw&Tipping2006*
Dubh-Lochan	38	20	57°17'26"N	4°26'7"W	SIPO	6	150	*Froyd 2006*
Black Lough	39	19	56°20'N	3°11'W	POLS	14	90	*Whittington et al 1991*
West Lomond	40	42	56°15'N	3°17'W	NOTK	15	395	*Edwards&Whittington 1997*
Crag Lough	43	11	55°00'21"N	02°21'57"W	POLS	9	250	*Dark 2005*
England:								
Walton Moss	41	22	55°2'4"N	2°44'27"W	SIEV	4	100	*Hughes et al 2000a*
Bolton Fell Moss	42	21	55°4'14"N	2°48'32"W	SIEV	22	110	*Barber et al 2003*
Talkin Tarn	44	40	54°55'19"N	2°42'38"W	POLS	9	130	*Langdon et al 2004*
Fenton Cottage	45	37	53°54'N	2°55'W	POLS	24	8.86	*Wells et al 1997*
Church Moss	46	39	53°14'20"N	2°30'17"W	NOTK	10	<25	*Hughes et al 2000b*
Sidlings Copse	50	13	51°46'54"N	1°11'48"W	POLS	5	<85	*Day 1991*
Cothill Fen	51	13	51°41'44"N	01°19'46"W	POLS	4	<85	*Day 1991*
Long Breach	52	24	51°3'42"N	3°41'15"W	NOTK	5	341	*Fyfe et al 2003*
Gourte Mire	53	24	51°3'42"N	3°41'15"W	NOTK	4	291	*Fyfe et al 2003*
Anstey's Combe	54	24	51°3'42"N	3°41'15"W	NOTK	6	282	*Fyfe et al 2003*
Black Ridge Brook	55	44	50°37'56"N	4°0'58"W	POLS	5	447	*Caseldine&Maguire 1986*
Rough Tor south	56	41	50°35'47"N	4°37'47"W	POLS	4	280	*Gearey et al 2000*
East Mor Monolith		41	NOTK	NOTK	POLS	3	280	*Gearey et al 2000*
Wales:								
Bryn y Castell	47	25	52°58'0"N	3°53'47"W	POLS (pc)	6	364	*Mighall&Chambers 1995*
Migneint	48	29	52°49'40"N	3°49'40"W	SIEV	5	440	*Ellis&Tallis 2001*
Esgryn Bottom	49	28	51°58'N	4°57'W	POLS	4	100	*Fyfe 2007*

5.2.2 Numerical analyses

The mean and standard error of the mean standardized charcoal values were calculated for 500 year calendar year time intervals covering the last 11 000 years for all charcoal records from across the British Isles (Bradshaw *et al.*, 2010). The relationship between upland and lowland regions of the British Isles was investigated by dividing the dataset into sites found above 200m asl and sites below 200m asl. The mean and standard error of the mean of the standardized charcoal values in 500 year calendar year time intervals was determined for both upland and lowland values. The relationships between charcoal and pollen data were explored using CANOCO version 4.54. Relationships between the pollen data were calculated using Detrended Correspondence Analysis (DCA) with the variables, charcoal and sample age, used to help interpret the resulting indirect gradient analysis ordination plots. The relationships between the 14 pollen types and their abundances were displayed on the first two DCA axes and the vectors of the two variables, charcoal and sample age, were added to these plots. Correlation coefficients between the pollen and charcoal data, with their significance based on a non-directional hypothesis were calculated for all pollen types. A square root transformation was applied to the pollen data prior to these calculations to minimize the non-linearity associated with percentage data (Bradshaw *et al.* 2010). The pollen-vegetation relationship was investigated using a variety of datasets including the complete British Isles Charcoal Database, the database split into upland and lowland sites, and split by time into two categories 0-4000 yrs BP and >4000 yrs BP.

5.3. Results

5.3.1 Temporal and Upland/Lowland patterns of charcoal deposition (Figures 5.2 & 5.3)

The charcoal record for the British Isles shows a significant degree of variance, with apparent chronological zones of charcoal deposition (Fig. 5.2). Maximum mean standardised charcoal values are achieved between 1000 and 1499 yrs

BP, during a phase of gradual increase in values. Minimum mean standardised charcoal values are observed in the early Holocene.

There is a considerable degree of variability in the mean standardised charcoal values between 12 000 and 9500 yrs BP, with minimum values during this period of 0.5 and 0.6 at 11 000-11 500 and 10 000-10 500 yrs BP respectively (Fig. 5.2), these values are the lowest observed throughout the entire record. A gradual decrease is then observed from 9500 to 8500 yrs BP from 0.16 to 0.12 (Fig 5.2). There is then a steady increase in mean standardized charcoal values from 8500 to 7500 yrs BP to a mean standardised charcoal value of 0.23.

The record then appears to enter another state of considerable variability between 7500 and 4500 yrs BP (Fig 5.2). There are two significant decreases in mean standardized charcoal values, the first at 6000-6500 yrs BP and the second at 4500-5000 yrs BP.

A steady increase in charcoal values can then be observed from 4500 yrs BP to 500 yrs BP, during this time period maximum mean standardised charcoal values for the entire record are achieved with a value of 0.25 at 1000-1500 yrs BP. The period of gradual decrease is then terminated by a significant decrease in charcoal to a value of 0.19 at 500 yrs BP (Fig 5.2).

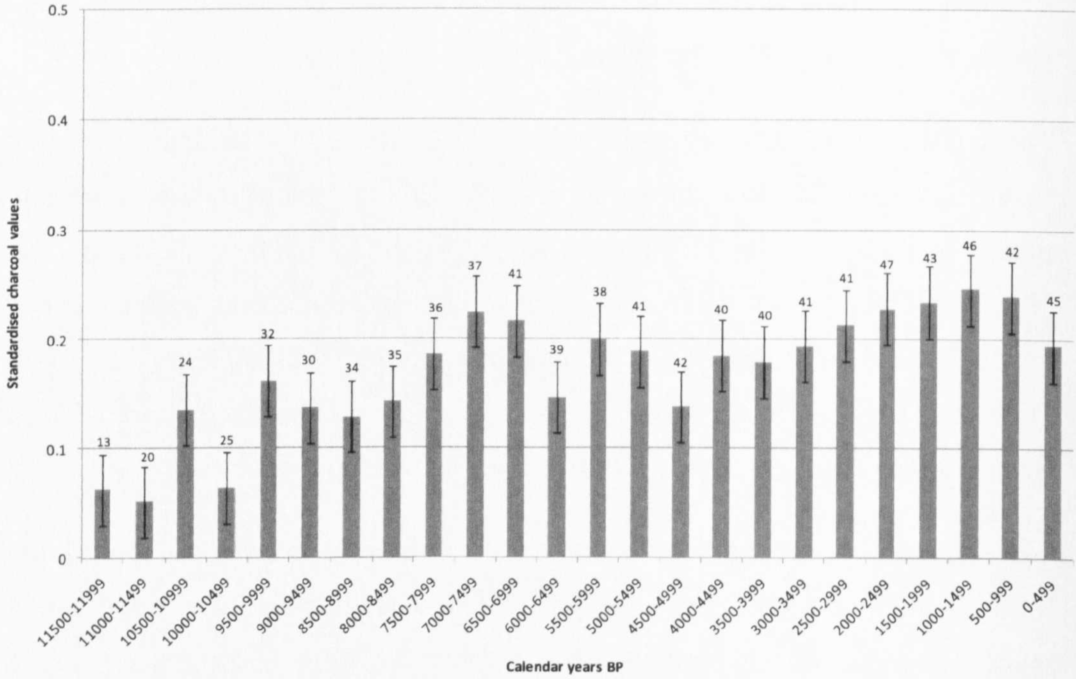


Figure 5.2: Mean standardized charcoal values in 500 year bins for the British Isles. Number of contributing sites to analysis indicated above column.

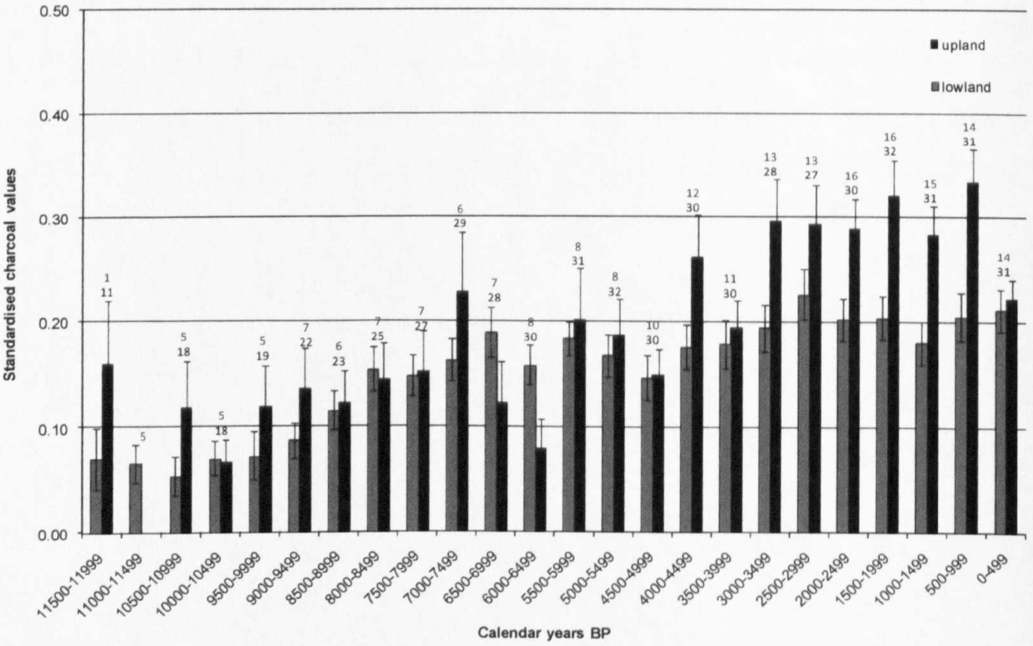


Figure 5.3: Upland (>200m a.s.l.) and Lowland (<200m a.s.l.) mean standardized charcoal values in 500 years bins for the British Isles. Sites contributing to the analysis are indicated in black and red, red being lowland and black, upland.

From 11 999 to 9500 yrs BP lowland burning was reasonably consistent, with mean standardized charcoal values at approximately 0.08 (Fig 5.3). Upland charcoal values are variable and during some periods considerably higher than lowland values. A gradual increase in both lowland and upland values begins at 10 000 yrs BP until 7000-7499 yrs BP, where there is a large increase in upland charcoal values to 0.23 (Fig 5.3).

There is then a marked difference in lowland and upland values with lowland values remaining reasonably steady, but upland values decrease markedly in a period of 1500 years, between 7000-7500 and 6000-6500 (Fig 5.3). Both records then return to values of approximately 0.2 at 5500-6000yrs BP, followed by a gradual decrease.

From 5000yrs BP to present, lowland values remain relatively constant, remaining about 0.2 (Fig 5.3). Upland values are significantly higher than lowland values from 3500 yrs BP until 500 yrs BP when values decrease sharply from a value of 0.33to a level similar to that of the lowlands, 0.22 (Fig 5.3).

5.3.2 Pollen-charcoal relationships (Figures 5.4, 5.5, 5.6 & 5.7)

To understand more clearly the nature of burning in the British Isles throughout the Holocene, pollen records were also collated for each of the sites in the charcoal database and the correlation of these pollen types to charcoal were then analyzed (Figure 5.4). Included in this figure are the values for southern Swedish sites analysed by Bradshaw *et al* (2010). As expected, in the Scandinavian record, *Pinus sylvestris, Betula* and *Calluna vulgaris* are positively correlated with charcoal, as these are shade-intolerant taxa that are favoured by fire. In the British record however, *Calluna vulgaris, Plantago lanceolata* and Poaceae are positively correlated with charcoal. These are taxa that suggest an open landscape and the presence of *Plantago lanceolata* suggests a strong positive correlation with human activity.

Figure 5.5 shows the pollen types displayed on the first two DCA axes, which accounted for 36.4% of the variance within the dataset. *Calluna vulgaris* and

Plantago lanceolata are separated from the rest of the taxa, each of which were most positively correlated with charcoal, and *Tilia cordata* is separated from other taxa by both axis 1 and 2.

There were significant positive correlations between standardised charcoal values and *Calluna*, *Plantago lanceolata*, Poaceae, *Fraxinus* and *Alnus* pollen abundances (Figures 5.4, 5.6 and 5.7). The most strongly positively correlated were *Calluna* and *Plantago lanceolata*, with correlation co-efficient values of 0.29 and 0.28 respectively(Figure 5.8 - 5.15). Throughout additional analyses by time and altitude, *Calluna* continues to be positively correlated with charcoal. Poaceae, *Fraxinus* and *Alnus* all have weaker positive correlations, ranging from 0.2 to 0.15. It would appear that there is a strong relationship between burning and an open landscape. *Quercus* is weakly positively correlated to standardised charcoal values, with a correlation coefficient value of 0.05 (Figure 5.4 & 5.6).

Table 5.2: Pollen types positively correlated with charcoal from sites included in the British Isles Charcoal Database (n = 2561). Correlation coefficients (R) and non-directional probabilities (P) with their significance levels ****<0.0001, ***<0.001, **<0.01.

Taxon	R	P
Calluna	0.2922	<0.0001****
Plantago	0.2791	<0.0001****
Poaceae	0.1967	<0.0001****
Fraxinus	0.1647	<0.0001****
Alnus	0.1525	<0.0001****
Quercus	0.0526	0.007758**

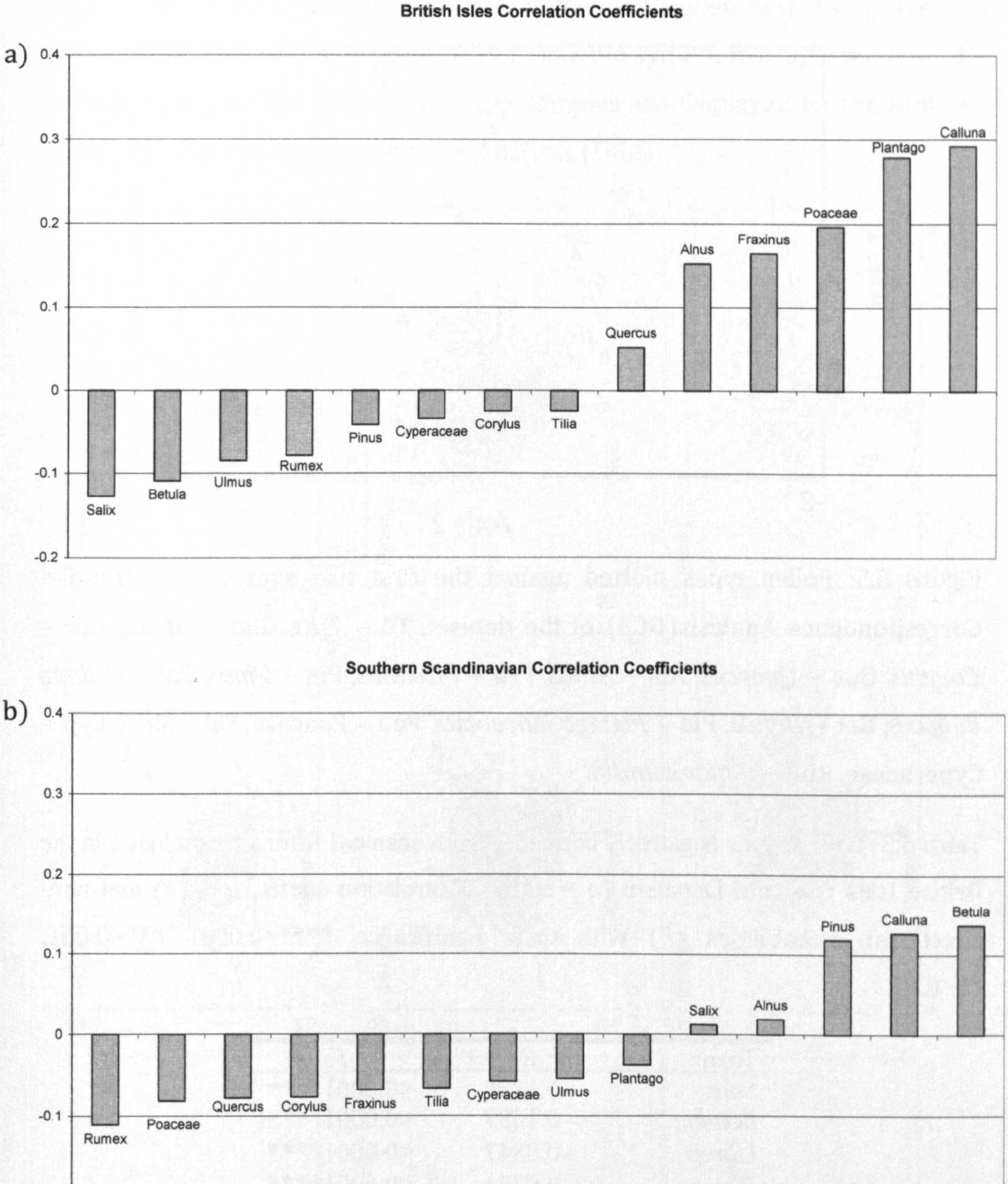


Figure 5.4: Graph showing charcoal and pollen type correlation coefficients, a) British Isles sites (n=2562), b) S. Sweden, n= 612 (*Bradshaw et al 2010*).

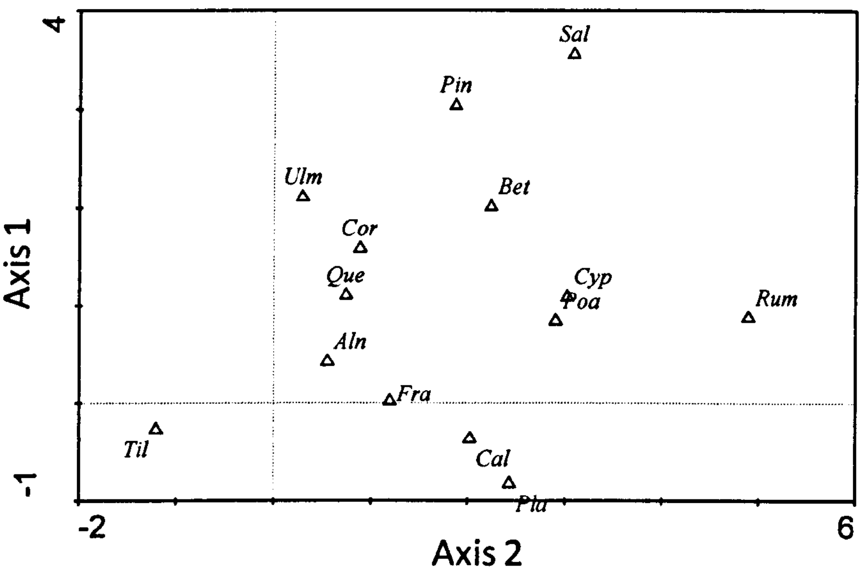
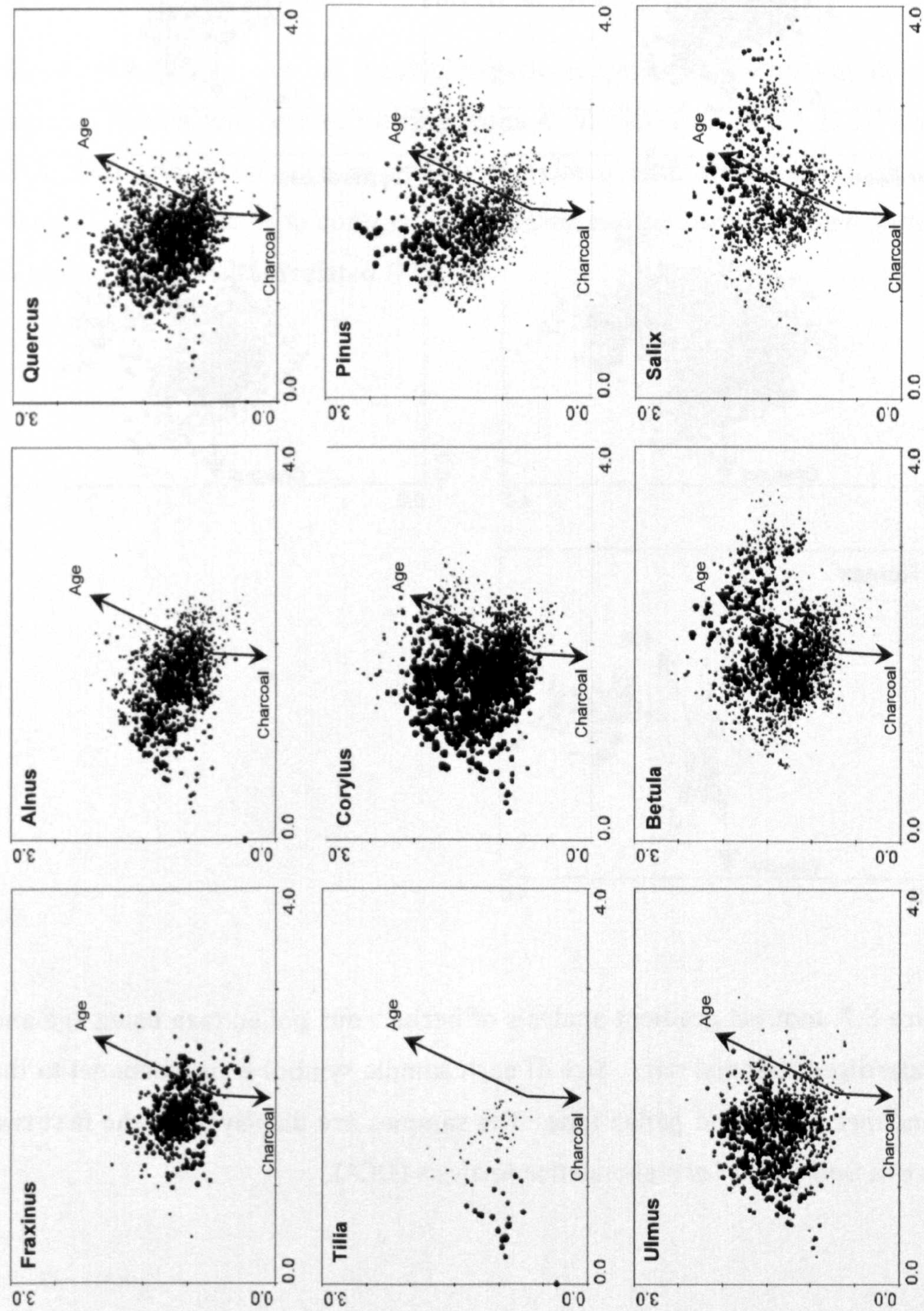


Figure 5.5: Pollen types plotted against the first two axes of a Detrended Correspondence Analysis(DCA) of the dataset. Til - *Tilia*, Ulm - *Ulmus*, Cor - *Corylus*, Que - *Quercus*, Aln - *Alnus*, Fra - *Fraxinus*, Pin - *Pinus*, Cal - *Calluna vulgaris*, Bet - *Betula*, Pla - *Platago lanceolata*, Poa - Poaceae, Sal - *Salix*, Cyp - Cyperaceae, Rum - *Rumex undiff.*

Table 5.3: Pollen types negatively correlated with charcoal from sites included in the British Isles Charcoal Database (n = 2561). Correlation coefficients (R) and non-directional probabilities (P) with their significance ****<0.0001 ***<0.001, **<0.01.

Taxon	*R*	*P*
Salix	-0.1276	<0.0001****
Betula	-0.1089	<0.0001****
Ulmus	-0.0847	<0.0001****
Rumex	-0.0784	<0.0001****

Figure 5.6: Indirect gradient analysis of wooded pollen taxa using age and standardised charcoal data. Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).



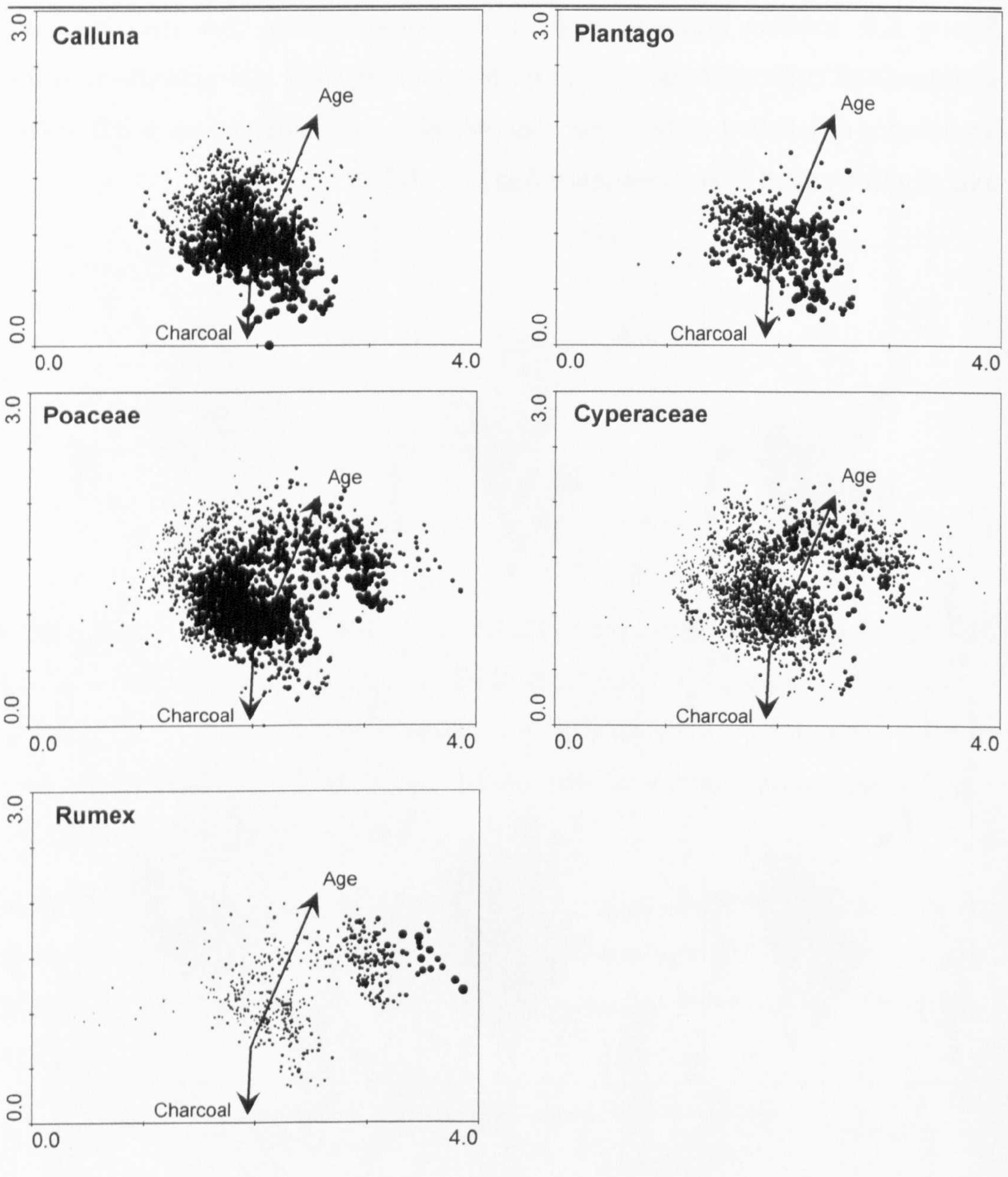


Figure 5.7: Indirect gradient analysis of herbaceous pollen taxa using age and standardised charcoal data. Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

The pollen species most negatively correlated with standardised charcoal values for the British Isles are *Salix* and *Betula*, -0.13 and -0.11, respectively (Figure 5.4 & 5.6). These results are different to those of the Swedish record, with *Betula* being strongly positively correlated with charcoal influx values (0.14) and *Salix*, weakly positively correlated (0.01) (Fig 5.4).

Ulmus and *Rumex*, are all weakly negatively correlated with standardised charcoal results, with values ranging from -0.08 and -0.02 (Fig 5.4, 5.6 & 5.7). Both *Salix* and *Betula* are negatively correlated with standardised charcoal result (Fig 5.4). This is in contrast to the Scandinavian record, where *Salix* and *Betula* are positively correlated (Fig 5.4).

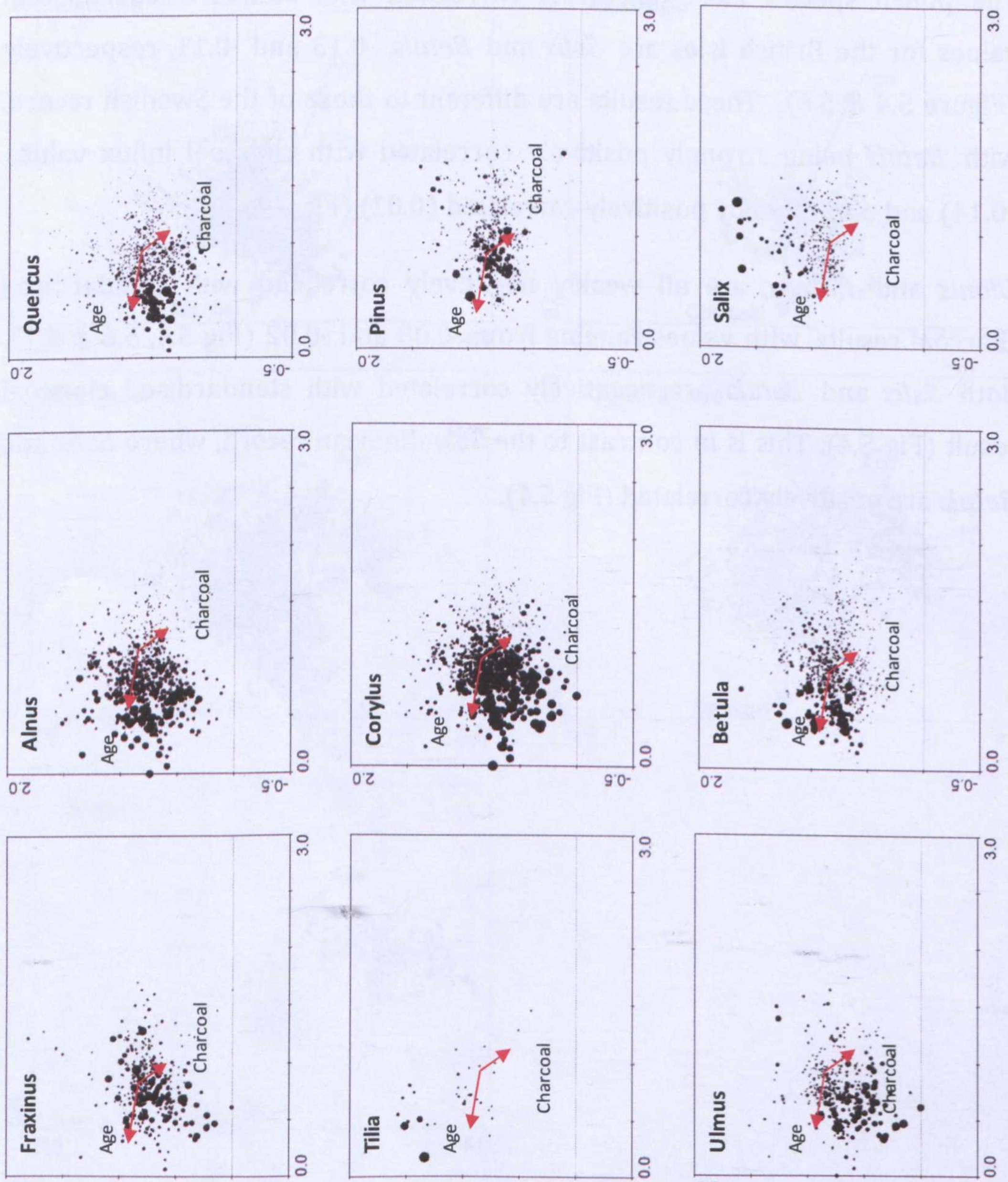


Figure 5.8: Indirect gradient analysis of wooded pollen taxa using age and standardised charcoal data for 0-4000 yrs BP dataset. Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

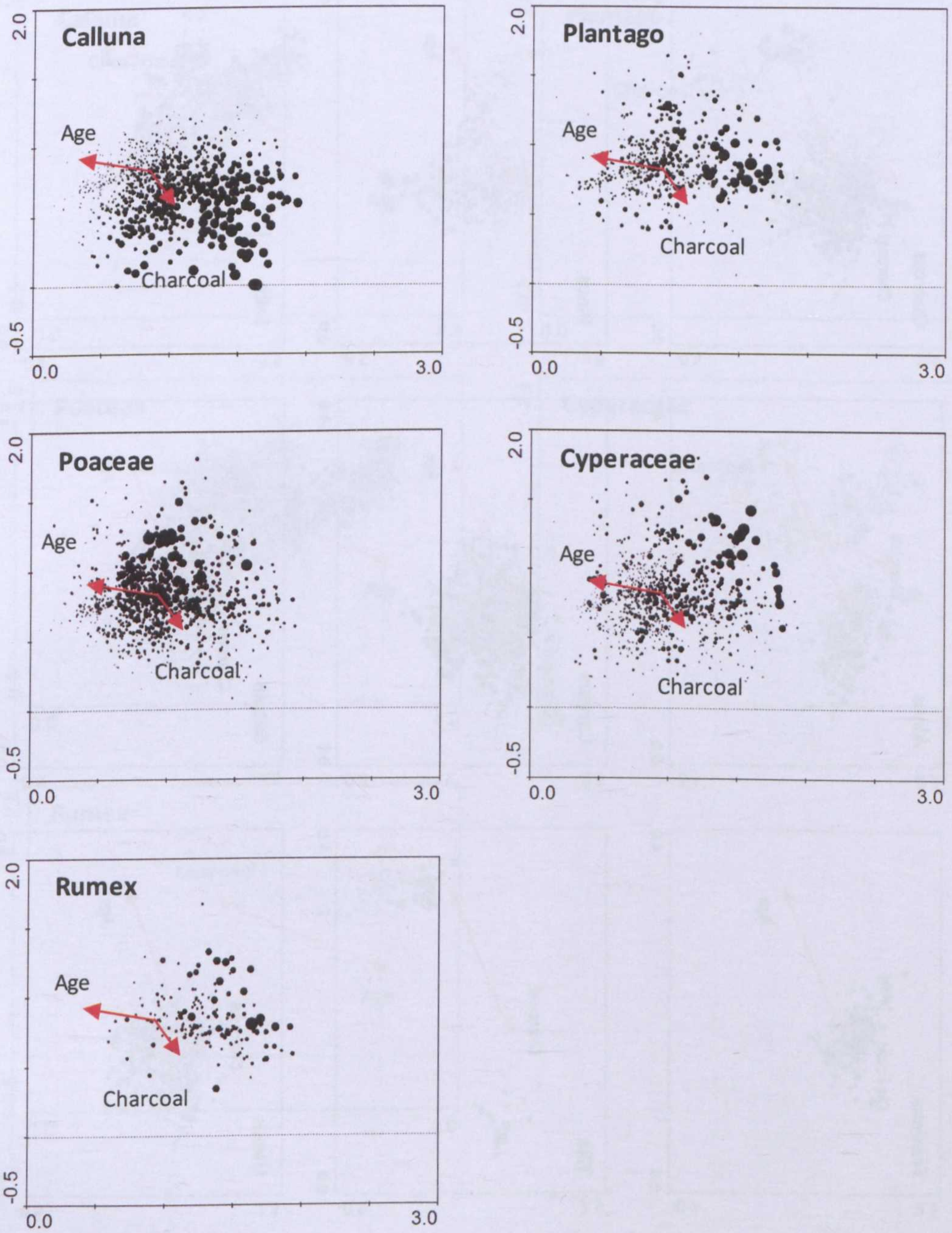


Figure 5.9: Indirect gradient analysis of herbaceous pollen taxa using age and standardised charcoal data for 0-4000 yrs BP dataset. Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

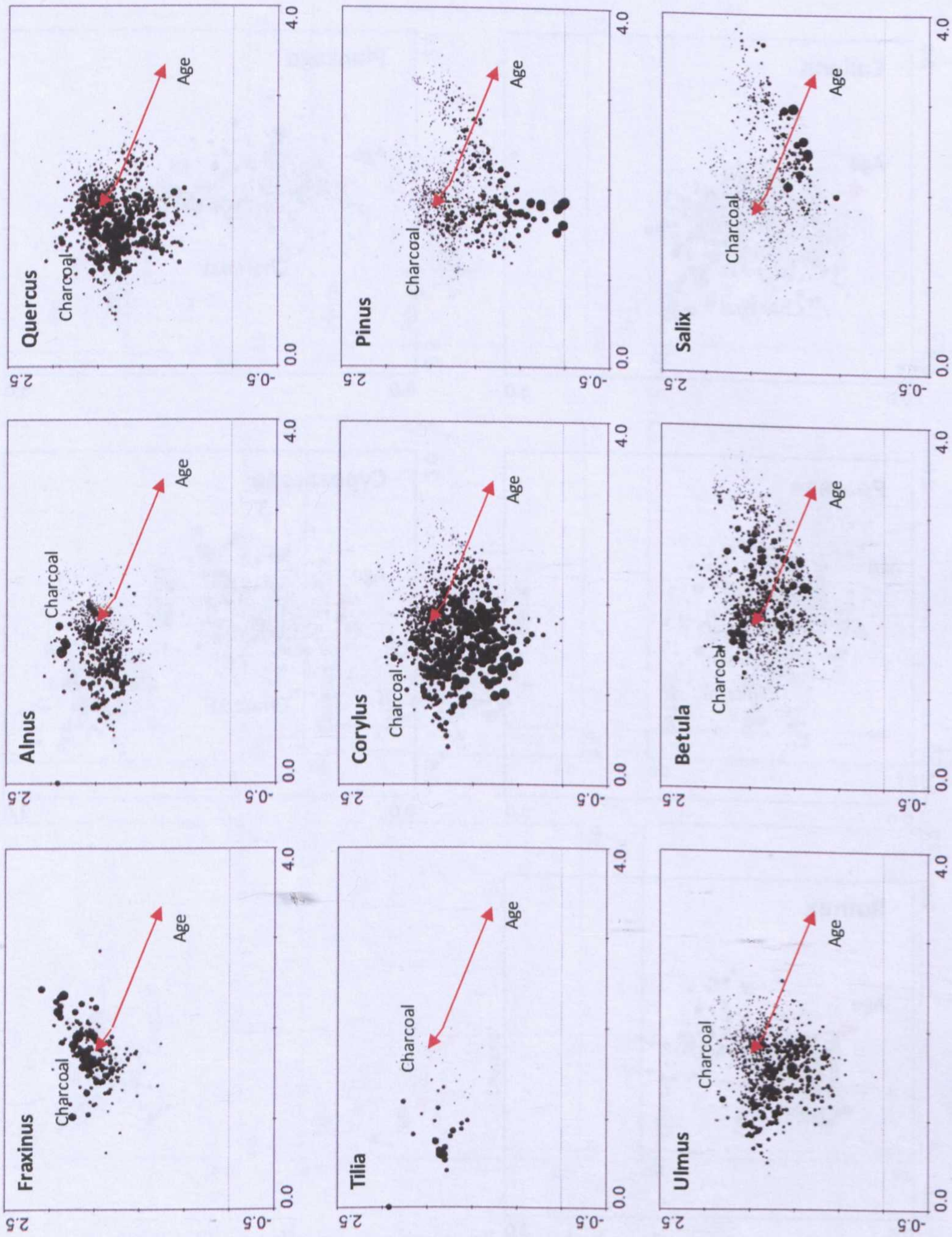


Figure 5.10: Indirect gradient analysis of wooded pollen taxa using age and standardised charcoal data for 4000 yrs BP and older dataset. Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

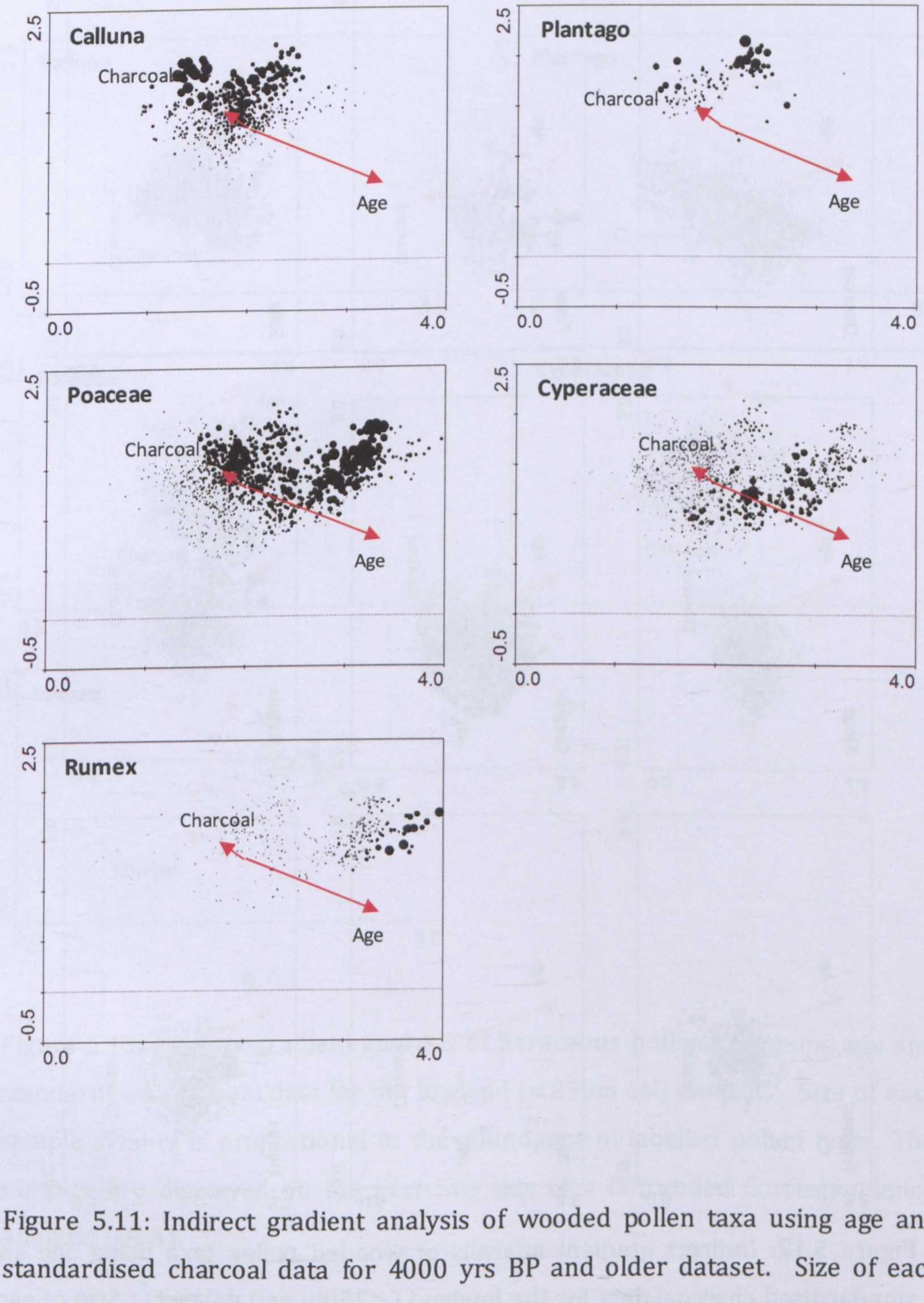


Figure 5.11: Indirect gradient analysis of wooded pollen taxa using age and standardised charcoal data for 4000 yrs BP and older dataset. Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

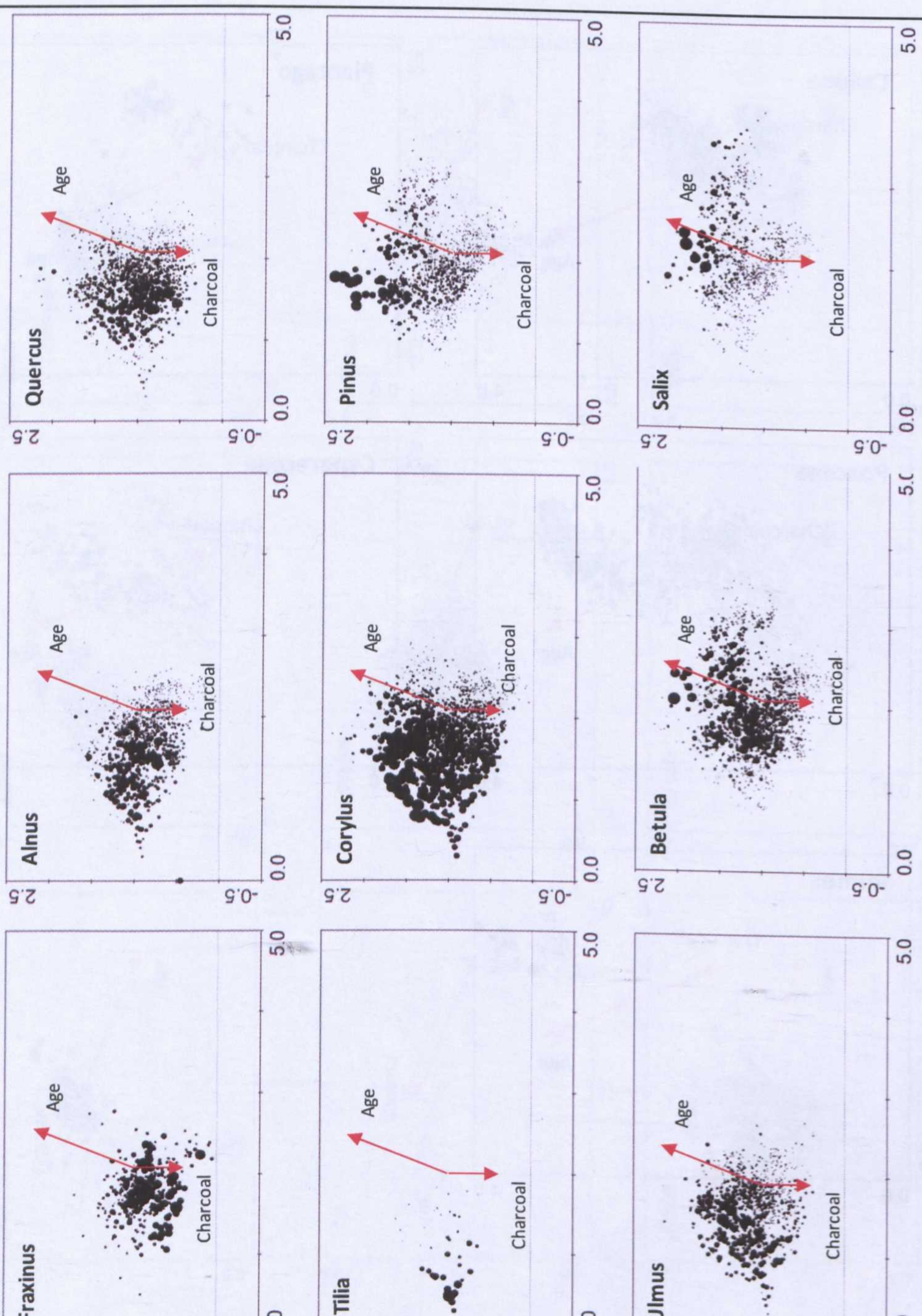


Figure 5.12: Indirect gradient analysis of wooded pollen taxa using age and standardised charcoal data for the lowland (<250m asl) dataset. . Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

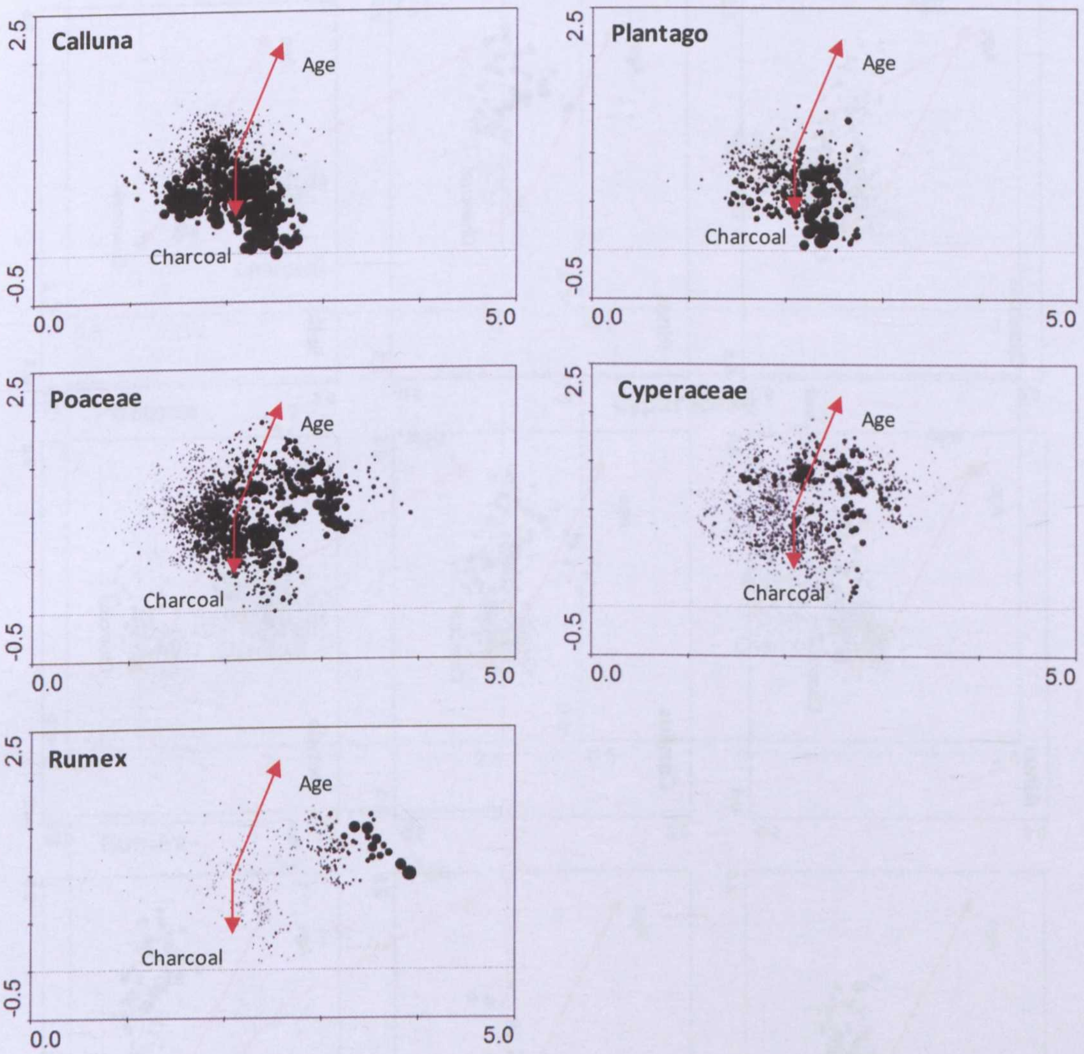


Figure 5.13: Indirect gradient analysis of heraceous pollen taxa using age and standardised charcoal data for the lowland (<250m asl) dataset. . Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

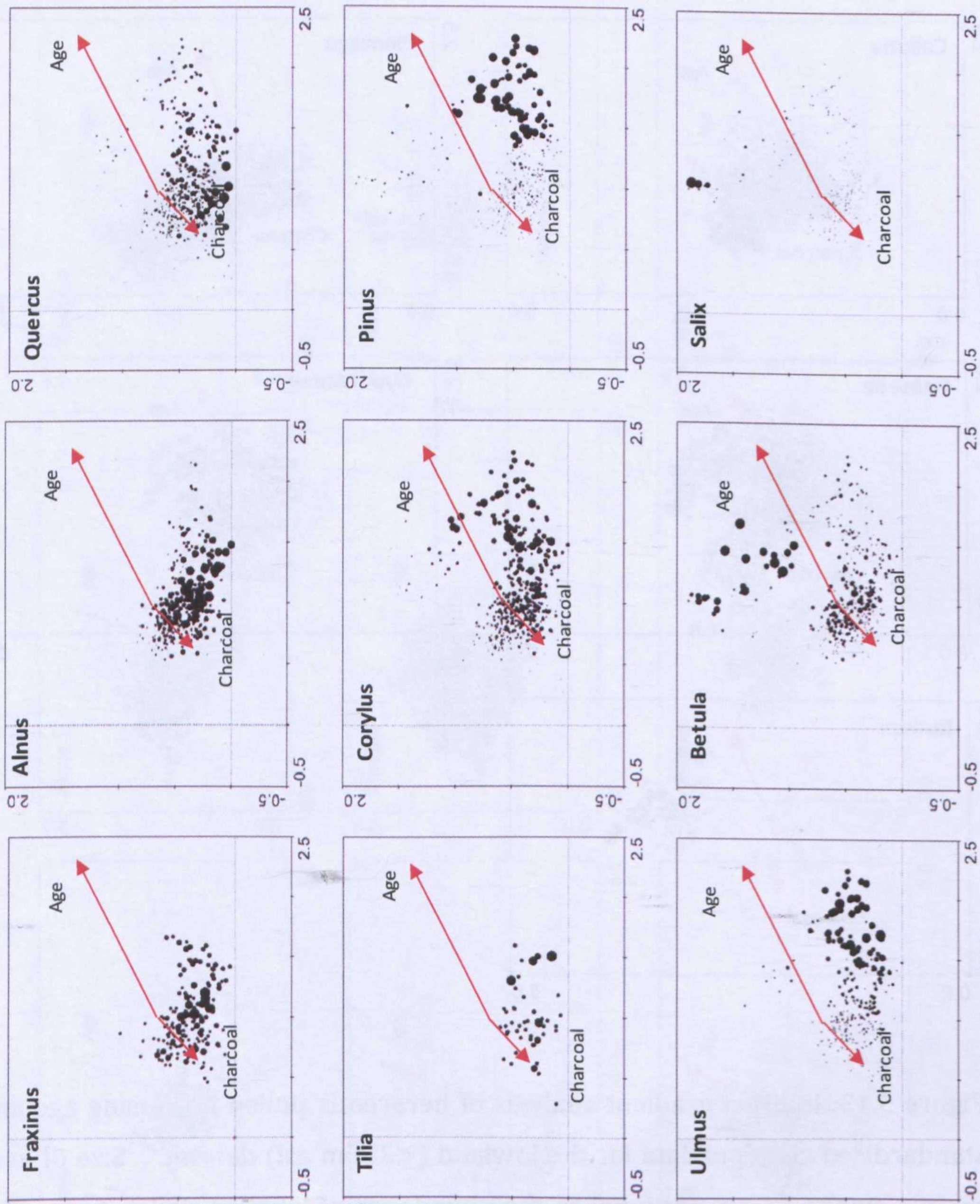


Figure 5.14: Indirect gradient analysis of wooded pollen taxa using age and standardised charcoal data for the upland (>250m asl) dataset. . Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

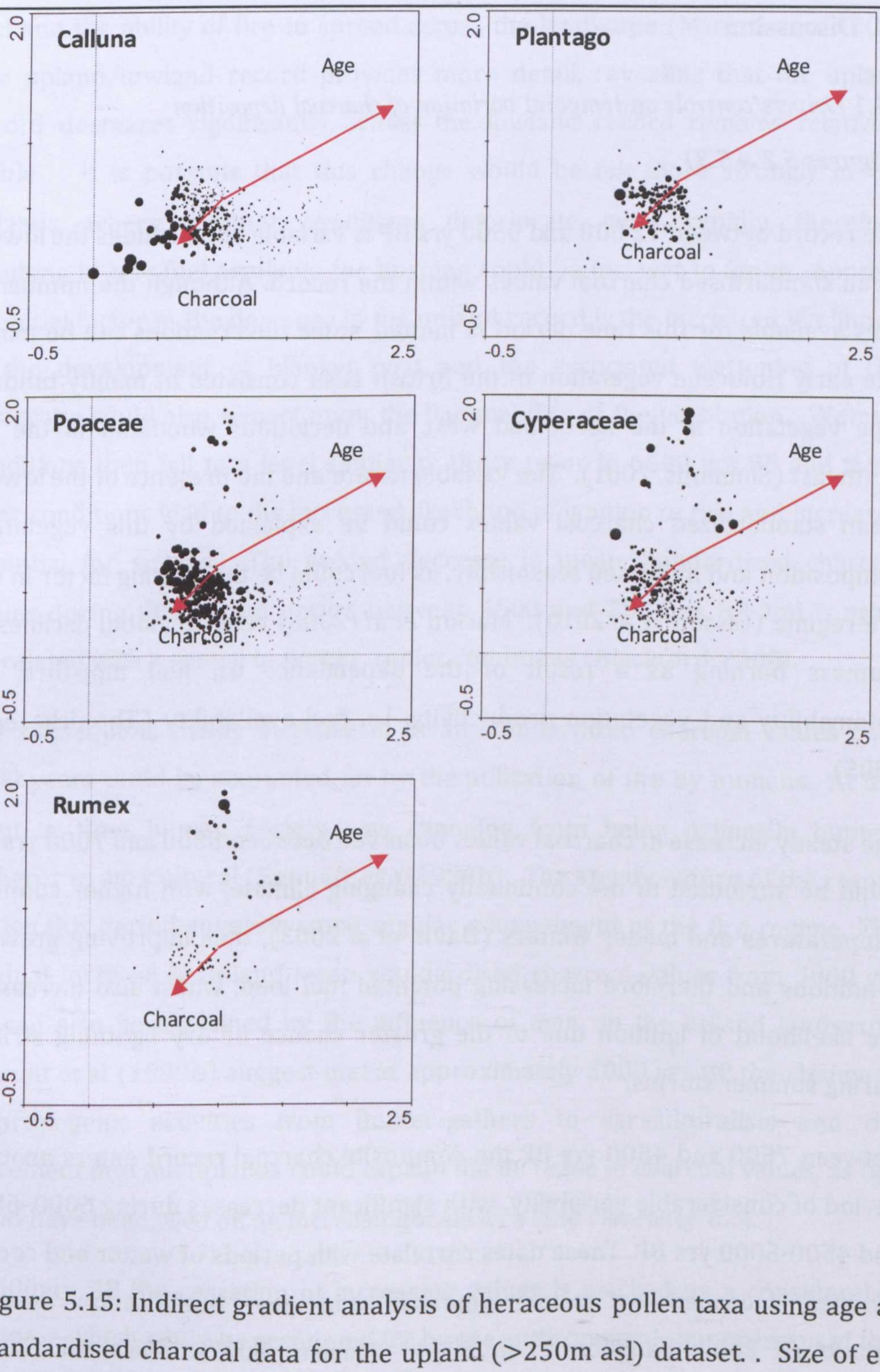


Figure 5.15: Indirect gradient analysis of heraceous pollen taxa using age and standardised charcoal data for the upland (>250m asl) dataset. . Size of each sample symbol is proportional to the abundance of labelled pollen type. The samples are displayed on the first two axis of a Detrended Correspondence Analysis (DCA).

5.4. Discussion

5.4.1 Drivers/controls on temporal variation of charcoal deposition (Figures 5.2 & 5.3)

The record between 12 000 and 9500 yrs BP is variable and includes the lowest mean standardised charcoal values within the record. Although the number of sites available for this time period is limited, some observations can be made. The early Holocene vegetation of the British Isles consisted of mainly tundra-type vegetation in the north and west, and deciduous woodland in the far southeast (Simmons, 2001). The variable nature and the presence of the lowest mean standardized charcoal values could be explained by this vegetation composition and increased seasonality, as fuel could be the limiting factor in the fire regime (Olsson *et al* 2010). Marlon *et al* (2008) refer to global declines in biomass burning as a result of the dependence on fuel moisture, i.e. flammability and vegetation productivity, i.e. fuel availability (Thonicke *et al* 2005).

The steady increase in charcoal values observed between 8500 and 7000 yrs BP could be attributed to the continually changing climate, with higher summer temperatures and milder winters (Davis *et al* 2003), thus improving growing conditions and therefore increasing potential fuel load, whilst also increasing the likelihood of ignition due to the greater chance of dry lightning strikes during summer storms.

Between 7500 and 4500 yrs BP the composite charcoal record enters another period of considerable variability, with significant decreases during 6000-6500 and 4500-5000 yrs BP. These dates correlate with periods of wetter and cooler climates, indicated by testate amoebae and peat humification records (Blackford 2000; Langdon *et al* 2003; Charman 2007). Blackford (2000) combined peat humification records from three sites in northern Scotland. The first decline in mean standardized charcoal values occurs at 6000-6499 yrs BP, this period of 500 years is marked by a sharp and short-spelled change to wetter conditions. A change to wetter conditions reduces the combustibility of fuel and the ability of fire to spread across the landscape (Marlon *et al* 2008). The upland/lowland record provides more detail, revealing that the upland record decreases significantly, whilst the lowland record remains relatively stable. It is possible that this change would be felt more strongly in the uplands, where weather conditions deteriorate more rapidly, therefore resulting in any fuel available for burning could be too wet to ignite. Another potential factor in the decrease in the upland record is the increased likelihood of the development of blanket peat and the associated wettening of the landscape could also impact upon the flammability of the vegetation. Wetness conditions then fall to a level similar to those prior to 6500 yrs BP and these drier conditions lead to the increased likelihood of ignition of fuel and increased potential for spread. The second decrease in mean standardized charcoal values during this period occurs between 4500 and 5000yrs BP and is again correlated with a return to wetter, cooler conditions (Blackford, 2000).

The subsequent steady increase in mean standardized charcoal values over 3000 years could be accounted for by the utilization of fire by humans. At this point in time human society was changing from being primarily hunter-gatherer to agricultural (Bennett *et al* 1990b). The steady nature of the record during this period suggests some regular management of the fire regime. The gradual increase in upland mean standardised charcoal values from 5000 yrs BP can also be explained by the influence of man on the upland landscape. Bennett et al (1990b) suggest that at approximately 5000 yrs BP the change in anthropogenic activities from hunter-gathers to agriculturalists and the movement into the uplands could explain the increase in charcoal values, as fire could have been used on an increasing scale as a land clearance tool.

At 500yrs BP the cessation of increasing values is marked by a considerable decrease which could be accounted for by the anthropogenic suppression of fire during recent centuries up to the present day. Marlon et al (2008) suggested that global biomass burning did not begin to decrease until the onset of the industrial revolution, when the landscape was subjected to intensive agricultural activities (arable and pastoral), leading to considerable fragmentation of the landscape and also the active management of fire in the environment, but this period of suppression began earlier in certain parts of Europe with long histories of organised agriculture (Granstrom and Niklasson 2008).

5.4.2 Pollen-charcoal relationships (Figures 5.4, 5.6 & 5.7)

The strong positive correlation between fire and *Calluna* abundance is consistent with the established ecology (Delarze *et al* 1992; Zackrisson 1977; Whitaker and Gimingham 1962) and palaeoecology of the species (Odgaard 1992). Burning creates ideal, open seed-bed conditions for *Calluna* regeneration and low-intensity burns stimulate shoots from existing plants (Whitaker and Gimingham, 1962, Delarze *et al.,* 1992). Research into Danish heathlands and burning found that there was a strong relationship between *Calluna* pollen and charcoal, suggesting that burning throughout the Holocene triggered and maintained the expansion of heathlands (Odgaard 1992). This relationship was also confirmed by Gaillard *et al* (1992) in southern Sweden, where modern pollen/land-use relationships were used as an aid in the reconstruction of past land-uses, here too *Calluna* was correlated with frequent burning of the landscape.

The (strong) positive correlation between Poaceae pollen abundance and standardised charcoal values is also consistent with the open conditions generated by the burning of vegetation. Poaceae and *Plantago lanceolata* are both strongly associated with other types of cultural disturbance such as mowing, trampling and grazing animals. Tinner *et al* (2005) observed positive correlations between *Alnus* pollen values and charcoal influx values. In the British Isles record, *Alnus* shows a strong positive correlation with standardised charcoal values, which could also be as a result of benefiting from increased light following fire (McVean, 1953; Tinner *et al* 1999).

Fraxinus shows a positive correlation with standardised charcoal values in contrast to previous studies which suggested that *Fraxinus* is quite sensitive to burning, which in extreme cases can lead to local extinction (Tinner *et al* 2000, Delarze *et al* 1992).

Quercus has a weak positive correlation which may be as a result of benefiting from fire. Mason (1992, pp. 122-128, cited in Mason 2000) suggests that deciduous *Quercus* appear to be fire-tolerant and that in some cases deciduous species of *Quercus* may actually benefit from fire. Regeneration could be aided by fire, as *Quercus* is a shade-intolerant species (Vera 2000, Jones 1959). Mature *Quercus* trees also have some resistance to low intensity fires as a result of their thick bark (Mason 2000), this too could account for the positive relationship between *Quercus* pollen and charcoal.

The positive correlation between *Betula* and *Salix*, and charcoal deposition in the Swedish record was attributed to increase in light conditions and therefore ability to colonise a recently burnt site, in the case of *Betula*, this was rapid (Atkinson 1992). A positive correlation in the British Isles record would also be expected (Tinner *et al* 2000, Delarze *et al* 1992), however a significant negative correlation is identified for both taxa. This result could suggest that much of the burning during the Holocene in the British Isles was not in wooded environments. If it was indeed taking place in wooded environments, a positive correlation would be expected, as death of some trees would allow for regeneration and competition of seedlings for recently exposed light.

Ulmus is a fire sensitive species and is damaged by fire, in some cases leading to local extinction (Tinner *et al* 2000), and so the weak negative correlation is expected. Delarze *et al* (1992) shows that in times of increased burning, *Rumex* is thought to be an indicator of cultural disturbance, particularly grazing in the landscape (Gaillard *et* al 1992). The DCA plot for *Rumex*, shows a distinct alignment of values in a direction not related to any other axis, it is likely that this could be the result of a grazing control, i.e. the defining axis, if it were possible to obtain information, would be grazing pressure. The weakly negative correlation with charcoal values and presence of other strongly positively correlated cultural indicator species, suggests that burning was not the only control on the landscape (Bradshaw *et al* 2010). The additional control may come in the form of grazing pressure, however at present there are few methods that can be employed to accurately ascertain direct evidence of grazing. *Pinus* has a strong positive relationship with burning in the Swedish record, however in the British Isles record it is weakly negatively correlated. This is possibly related to the lack of dominance of *Pinus* in the British Isles landscape through the Holocene and therefore little dominance in the fire record. Pine in the UK probably burnt in the early Holocene but the Scottish Pine forests burnt less in the later Holocene yet are well represented in the pollen record. Pine has recently been planted in plantations where fire is suppressed.

5.5 Conclusions

There are numerous records of burning during the Holocene in the British Isles. The collation of these records has enabled an assessment of the spatio-temporal relationships. It is apparent that fire has been present throughout the Holocene, in varying intensities. The early Holocene saw few records of burning, with low charcoal values. Climatic conditions are likely to have determined this, being particularly unfavourable for vegetation growth and therefore lack of fuel (Seppä and Birks 2002). The mid-Holocene is a time of variation, mean standardized charcoal values fluctuate from near record minima to relatively high values. Variable climatic conditions, in particular precipitation, play a vital role in the ignition of a fire (Marlon *et* al 2008) and so with wet shifts (Blackford 2000) in an otherwise improving climate, fire would be limited by fuel moisture. The late Holocene is a period dominated by human influence. The record becomes more stable and a steady increase in mean standardized charcoal values is observed, this stability suggests a degree of management of the environment. The past 500years have seen a sharp decrease in charcoal values, likely to be a result of recent fire suppression (Marlon *et al* 2008).

The separation of the charcoal record into lowland and upland environments has provided insight into the differences in fire regimes. Both lowland and upland areas have similar, low values in the early Holocene. The mid-Holocene is the only time period to see lowland standardised charcoal values higher than upland standardised charcoal values, possibly attributed to wetter conditions and higher sensitivity of the uplands to these conditions. The late Holocene (3000 - 500 yrs BP) sees upland values increase and the difference between upland and lowland values is greater, this could be attributed to the exploitation of the uplands by agricultural communities encouraging a change to fire sensitive *Calluna* heaths and moors. Climatic downturn could also explain the difference in lowland and upland values, with upland areas more susceptible to the expansion of blanket peat.

Pollen-charcoal relations support the expected correlation between burning and *Calluna vulgaris*. Strong positive correlations between *Calluna*, Poaceae and *Plantago lanceolata* suggest that there is a strong relationship between British heathlands and fire, and the presence of cultural indicators supports the likelihood of human influence. Negative correlations between *Betula* and *Salix*, and charcoal values suggest limited fire in the wooded environment and dominance in heathland and open areas.

These results give an idea of the role fire has had on the environment in the British Isles and to some extent an insight into the controls of fire events, however more reliable climatic data are needed to solve the question of anthropogenic or naturally occurring fire?

5.6 References

Atkinson, M.D. (1992) *Betula pendula* Roth (*B. Verrucosa* Ehrh.) and *B. Pubescens* Ehrh., *Journal of Ecology,* **80**, 837-870.

Barber, K.E., Chambers, F.M., Maddy, D. (2003) Holocene palaeoclimates from peat stratigraphy: macrofossil proxy climate records from three oceanic raised bogs in England and Ireland, *Quaternary Science Reviews,* 22, 521-539.

Bennett, K.D. (1998) Psimpoll 4.10 and Pscomb 1.03 – C programs for plotting pollen diagrams and analysing pollen data.
http//www.kv.geo.uu.se/psimpoll_manual/4.00/psimpoll.html

Bennett, K.D., Boreham, S., Sharp., M.J., Switsur, V.R. (1992) Holocene History of Environment, Vegetation and Human Settlement on Catta Ness, Lunnasting, Shetland, *Journal of Ecology,* 80, 2, 241-273.

Bennett, K.D., Fossitt, J.A., Sharp, M.J., Switsur, V.R. (1990a) Holocene Vegetational and Environmental History at Loch Lang, South Uist, Western Isles, Scotland, *New Phytologist,* 114, 2, 281-298.

Bennett, K. D., Simonson, W.D., Peglar, S.M. (1990b) Fire and Man in Post-Glacial Woodlands of Eastern England, *Journal of Archaeological Science,* 17, 635-642.

Blackford, J. (2000) Palaeoclimatic records from Peat bogs, *TREE,* Vol. 15, No. 5.

Bowman, M.J.S. *et al* (2009) Fire in the Earth System, *Science,* **324**, 481

Bradshaw, R.H.W., Lindblach, M., Hannon, G. E. (2010) The role of fire in southern Scandinavian forests during the late Holocene, *International Journal of Wildland Fire, (in press).*

Brown, A.G., Hatton, J., O'Brien, C.E., Selby, K.A., Langdon, P.G., Stuijts, I., Caseldine, C.J. (2005) Vegetation, landscape and human activity in Midland Ireland: mire and lake records from the Lough Kinale-Derragh Lough area, Central Ireland, *Vegetation History and Archaeobotany,* 14, 81-98.

Bunting, M.J. (1996) The development of heathland in Orkney, Scotland: pollen records from Loch of Knitchen (Rousay) and Loch of Torness (Hoy), *The Holocene*, **6**, 193.

Bunting, M.J. (1994) Vegetation history of Orkney, Scotland; pollen records from two small basins in west Mainland, *New Phytologist*, 128, 771-792.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S., Prairies, Y.T. (2001) Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition trigger the fire regime? *Holocene*, **89**, 930-946.

Caseldine, C.J., Maguire, D.J. (1986) Lateglacial/Early Flandrian Vegetation change on Northern Dartmoor, South-West England, *Journal of Biogeography*, 13, 3, 255-264.

Charman, D. J. (2007) Summer water deficit variability controls on peatland water-tables: implications for Holocene palaeoclimate reconstructions, *Holocene*, **17**, 217-227.

Colombaroli, D., Marchetto, A., Tinner, W. (2007) Long-term interactions between Mediterranean climate, vegetation and fire regime at Lago di Massaciuccoli (Tuscany, Italy), *Journal of Ecology*, **95**, 755-770.

Dark, P. (2005) Mid- to late-Holocene vegetational and land-use change in the Hadrian's Wall region: a radiocarbon-dated pollen sequence from Crag Lough, Northumberland, England, *Journal of Archaeological Science*, 32, 601-618.

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J. and data contributors (2003) The temperature of Europe during the Holocene reconstructed from pollen data, *Quaternary Science Reviews*, Vol. 22, Issues 15-17, 1701-1716.

Day, S.P. (1991) Post-Glacial Vegetational History of the Oxford Region, *New Phytologist*, 119, 3, 445-470.

Delarze, R., Caldelari, D., Hainard, P. (1992) Effects of Fire on Forest Dynamics in Southern Switzerland, *Journal of Vegetation Science*, **3**, 1, 55-60.

Edwards, K.J., Langdon, P.G., Sugden, H. (2007) Seperating climatic and possible human impacts in the early Holocene: biotic response around the time of the 8200 cal. Yr BP event, *Journal of Quaternary Science*, 22, 1, 77-84.

Edwards, K.J., Whittington, G., Robinson, M., Richter, D. (2005) Palaeoenvironments, the archaeological record and cereal pollen detection at Clickimin, Shetland, Scotland, *Journal of Archaeological Science*, 32, 1741-1756.

Edwards, K.J., Whittington, G. (2000) Multiple charcoal profiles in a Scottish lake: taphonomy, fire ecology, human impact and interference, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **164**, 67-86.

Edwards, K.J., Whittington, G. (1997) A 12 000-year record of environmental change in the Lomond Hills, Fife, Scotland: vegetational and climatic variability, *Vegetation History and Archaeobotany*, 6, 133-152.

Edwards, K.J., Berridge, J.M.A., (1994) The Late-Quaternary Vegetational History of Loch a'Bhogaidh, Rinns of Islay, S.S.S.I., Scotland, *New Phytologist*, 128, 4, 749-770.

Ellis, C.J., Tallis, J.H. (2001) Climatic control of peat erosion in a North Wales blanket mire, *New Phytologist*, 152, 313-324.

Ellis, C.J., Tallis, J.H. (2000) Climatic control of blanket mire development at Kentra Moss, north-west Scotland, *Journal of Ecology*, 88, 869-889.

Foley, J.A., Prentice, I.C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., Haxeltime, A. (1996) An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics, *Global Biogeochemical Cycles*, **10**, 4, 603-628.

Fossit, J.A. (1996) Late Quaternary vegetation history of the Western Isles of Scotland, *New Phytologist*, 132, 171-196.

Fossit, J.A. (1994) Late Glacial Holocene vegetation history of western Donegal, Ireland, *Proceedings of the Royal Irish Academy*, 94B, 1, 1-31.

Froyd, C.A., (2006) Holocene fire in the Scottish Highlands: evidence from macroscopic records, *The Holocene*, 16, 235-249.

Fyfe, R. (2007) The importance of local-scale openness within regions dominated by closed woodland, *Journal of Quaternary Science*, 22, 6, 571-578.

Fyfe, R.M., Brown, A.G., Rippon, S.J. (2003) Mid- to late-Holocene vegetation history of Greater Exmoor, UK: estimating the spatial extent of human-induced vegetation change, *Vegetation History and Archaeobotany*, 12, 215-232.

Gaillard, M.-J., Birks, H.J.B., Emanuelsson, U., Berglund, B.E. (1992) Modern pollen/land-use relationships as an aid in the reconstruction of past land-uses and cultural landscapes: an example from south Sweden, *Vegetation History and Archaeobotany*, 1, 3-7.

Granström, A., Niklasson, M. (2008) Potentials and limitations for human control over historic fire regimes in the boreal forest, *Philosophical Transactions of the Royal Society B*, **363**, 2353-2358.

Gearey, B.R., Charman, D.J., Kent, M. (2000) Palaeoecological Evidence for the Prehistoric settlement of Bodmin Moor, Cornwall, Southwest England. Part I: The Status of woodland and Early Human Impacts, *Journal of Archaeological Science*, 27, 423-438.

Hirons, K.R., Edwards, K.J. (1990) Pollen and Related Studies at Kinloch, Isle of Rhum, Scotland, with Particular Reference to Possible Early Human Impacts on Vegetation, *New Phytologist*, 116, 4, 715-727.

Hirons, K.R., Edwards, K.J. (1986) Events at and Around the First and Second Ulmus Declines: Palaeoecological Investigations in Co. Tyrone, Northern Ireland, *New Phytologist*, **104**, 1, 131-153.

Huang, C.C. (2002) Holocene landscape development and human impact in the Connemara Uplands, Western Ireland, *Journal of Biogeography*, 29, 153-165.

Hughes, P.D.M., Mauquoy, D., Barber, K.E., Langdon, P.G. (2000a) Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England, *The Holocene*, 10, 4, 465-479.

Hughes, P.D.M., Kenward, H.K., Hall, A.R., Large, F.D. (2000b) A high-resolution record of mire development and climatic change spanning the Late-glacial-Holocene boundary at Church Moss, Davenham (Cheshire, England), *Journal of Quaternary Science*, 15, 7, 697-724.

Jeličić, L., O'Connell, M. (1992) History of vegetation and land use from 3200 B.P. to the present in the north-west Burren, a karstic region of western Ireland, *Vegetation History and Archaeobotany*, 1, 119-140.

Jones, E.W. (1959) Biological flora of the British Isles. *Quercus petraea, Quercus robur L., Journal of Ecology*, 47, 67, 169-222.

Langdon, P.G., Barber, K.E., Lomas-Clarke, S.H. (2004) Reconstructing climate and environmental change in northern England through chironomid and pollen analyses: evidence from Talkin Tarn, Cumbria, *Journal of Palaeolimnology*, 32, 197-213.

Langdon, P.G., Barber, K.E., Hughes, P.D.M. (2003) A 7500-year peat-based palaeoclimate 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.

Larsen, C.P.S., Macdonald, G.M. (1995) Relations between tree-ring widths, climate, and annual area burned in the boreal forest of Alberta, *Canadian Journal of Forest Research*, 25, 11, 1746-1755.

Leira, M., Cole, E.E., Mitchell, F.J.G. (2007) Peat erosion and atmospheric deposition impacts on an oligotrophic lake in eastern Ireland, *Journal of Palaeolimnology*, 38, 49-71.

Lindblach, M., Bradshaw, R.H.W. (1998) The origin of present forest composition and pattern in southern Sweden,*Journal of Biogeography*, **25**, 463-477.

Lynch, J.A., Hollis, J.L., Feng Sheng Hu (2004) Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska, *Journal of Ecology*, **92**, 477-498.

Lynch, J.A., Clark, J.S., Bigeloq, N.H., Edwards, M.E., Finney, B.P. (2003) Geographic and temporal variations in fire history in boreal ecosystems of Alaska, *Journal of Geophysical Research*, **108**.

Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., Prentice, I. C. (2008) Climate and human influences on global biomass burning over the past two millennia, *Nature Geoscience*, Vol. 1.

Marlon, J.R., Bartlein, P.J., Whitlock, C. (2006) Fire-fuel-climate linkages in the northwestern USA during the Holocene, *Holocene*, **16**, 8, 1059-1071.

Mason, S.L.R., (2000) Fire and Mesolithic subsistence - managing oaks for acorns in northwest Europe? *Palaeogeography, Palaeoclimatology, Palaeoecology*, 164, 139-150.

Mason, S.L.R. (1992) Acorns in human subsistence. Ph.D. Thesis, University College London (unpublished).

McVean, D.N. (1953) Alnus glutinosa (L.) Gaerthn. *Journal of Ecology*, 41, 447-466.

Mighall, T.M., Timpany, S., Blackford, J.J., Innes, J.B., O'Brien, C.E., O'Brien, W., Harrison, S. (2008) Vegetation change during the Mesolithic and Neolithic on the Mizen Peninsula, Co. Cork, south-west Ireland, *Vegetation History and Archaeobotany*, 17, 617-628.

Mighall, T.M., Chambers, F.M.(1995) Holocene Vegetation History and Human Impact at Bryn y Castell, Snowdonia, North Wales, *New Phytologist*, **130**, 2, 299-321.

Mitchell, F.J.G. (1998) The Vegetational History of the Killarney Oakwoods, SW Ireland: Evidence from Fine Spatial Resolution Pollen Analysis, *Journal of Ecology*, 76, 2, 415-436.

Molloy, K., O'Connell, M. (1991) Palaeoecological investigations towards the reconstruction of woodland and land-use history at Lough Sheeauns, Connemara, western Ireland, *Review of Palaeobotany and Palynology*, 67, 75-113.

Moore, J. (2000) Forest fire and human interaction in the early Holocene woodlands of Britain, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **164**, 125-137.

O'Connell, M.O., Huang, C.C., Eicher, U. (1999) Multidiciplinary investigations, including stable-isotope studies, of thick Late-glacial sediments from Tory Hill, Co. Limerick, western Ireland, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 147, 169-208.

Odgaard, B. V. (1992) The fire history of Danish heathland areas as reflected by pollen and charred particles in lake sediments. *The Holocene*, 16, 731-741.

Olsson, F., Gaillard, M.-J., Lemdahl, G., Greisman, A., Lanos, P., Marguerie, D., Marcoux, N., Skoglund, P., Wäglind, J. (2010) A continuous record of fire covering the last 10,500 calendar years from souther Sweden – The role of climate and human activities, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **291**, 128-141.

Peterken, G.F. (1993) *Woodland conservation and management*, 2nd ed, London, Chapman & Hall.

Power, M.J. & Palaeofire Working Group (2008) Changes in fire regimes since the last Glacial Maximum: an assessment based on global synthesis and analysis of charcoal data, *Climate Dynamics*, **30**, 887-907.

Rackham, O. (1986) *The history of the countryside*, J.M. Dent.

Schimmel, J., Granstrom, A. (1996) Fire Severity and Vegetation Response in the Boreal Swedish Forest, *Ecology*, **77**, 5, 1436-1450.

Scott, A.C., Cripps, J.A., Collinson, M.E., 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., Birks, H.J.B. (2002) Holocene Climate Reconstructions from the Fennoscandian Tree-Line Area Based on Pollen Data from Toskaljavri, *Quaternary Research*, **57**, 191-199.

Shaw, H., Tipping, R. (2006) Recent pine woodland dynamics in east Glen Affric, northern Scotland, from highly resolved palaeoecological analyses , *Forestry*, **79**, 3.

Simmons, I.G., Innes, I.G. (1988) Late Quaternary vegetational history of the North York Moors. X. Investigations on East Bilsdale Moor, *Journal of Biogeography*, **15**, 299-324.

Simmons, I.G. (2001) *An Environmental History of Great Britain: From 10, 000 Years Ago to the Present*, Edinburgh, Edinburgh University Press.

Stuiver, M., Reimer, P. (1993) Extended ^{14}C database and revised CALIB radiocarbon calibration program, *Radiocarbon*, **35**, 215-230.

Thonicke, K., Prentice, I.C. (2005) Modelling glacial-interglacial changes in global fire regimes and pyrogenic trace gas emissions, *Global Biogeochemical Cycles*, **19**.

Thonicke, K., Venevsky, S., Sitch, S., Cramer, W. (2001) The role of fire for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model, *Global Ecology & Biogeography*, **10**, 661-677.

Tinner, W., Conedera, M., Ammann, B., Lotter, A.F. (2005) Fire ecology north and south of the Alps since the last ice age, *The Holocene*, **15**, **8**, **1214-1226**.

Tinner, W., Conedera, M., Gobet, E., Hubschmind, P., Wehrli, M., Ammann, B. (2000) A palaeoecological attempt to classify fire sensitivity of trees in the southern Alps, *The Holocene*, 10, 565.

Tinner, W.,Hubschmid, P., Wehrli, M., Ammann, B., Conedera, M. (1999) Long-term forest fire ecology and dynamics in southern Switzerland, *Journal of Ecology*, 87, 273-289.

Vera, F.W.M. (2000) *Grazing Ecology and Forest History*, Wallingford, CABI Publishing.

Wells, C., Huckerby, E., Hall, V. (1997) Mid- and late-Holocene vegetation history and tephra studies at Fenton Cottage, Lancashire, U.K., *Vegetation History and Archaeobotany*, 6, 153-166

Whitaker, E, Gimingham, C.H. (1962) The effects of fire on regeneration of *Calluna vulgaris* (L.) Hull. from seed. *Journal of Ecology*, 50. 815-822.

Whittington, G., Edwards, K.J., Cundill, P.R. (1991) Late- and Post-Glacial Vegetational Change at Black Loch, Fife, Eastern Scotland – a Multiple Core Approach, *New Phytologist*, 118, 1, 147-166.

Whitlock, C., Shafer, S.L., Marlon, J. (2003) The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management, *Forest Ecology and Management*, 178, 5-21.

Woodward, F.I., Smith, T.M., Emanuel, W.R. (1995) A global land primary productivity and phytogeography model, *Global Biogeochemical Cyclyes*, 9, 471-490.

Zackrisson, O. (1977) Influence of forest fires on north Swedish boreal forest, *Oikos*, 29, 22-32.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

This research has looked at the changing vegetation structure and composition of two sites of specific interest in the British Isles, an ancient upland oakwood and an example of a deteriorating wood-pasture system. The research has attempted to identify the disturbance mechanisms active within these areas in the past and determine their effects on present vegetation structure, with one key mechanism being identified, fire. Investigation into fire as a disturbance mechanism across the British Isles was studied in an attempt to evaluate its effects on vegetation structure and origins, in terms of natural or anthropogenic ignition.

Investigation of an ancient oakwood revealed that the dominance of oak is recent and likely to be as a result of significant disturbance of the woodland in the recent past, such as grazing and coppicing. The woodland appears to have gone through three phases of development, approximately 1700 years BP, it was a diverse woodland composed of *Quercus*, *Alnus*, *Betula* and *Fraxinus*. There then appears to have been an opening of the woodland canopy and an increase in herbaceous taxa in the pollen record, likely to be as a result of disturbance (grazing, coppicing). In the late 19th century the woodland regenerates and the dominance of Quercus occurs. This dominance is likely to have been as a result of selective management of the woodland for resources purposes and also a decrease in soil conditions, creating unfavourable conditions for species present in the previous wooded phase. The continued presence of wooded species at the site means that it is likely that Wistman's Wood is an ancient secondary semi-natural woodland, as a result of disturbance and fragmentation prior to AD 1650 and continued, less intense disturbance and management post AD 1650.

The use of a Mor humus profile has proven effective, especially considering its limited usage in the recent past amongst the palaeoecological community. Radiocarbon dating of the 37cm core was successful by targeting of the humin fraction excluding potentially mobile humic and fulvic acid and through the careful removal of rootlet. Reconstruction of the vegetation history by pollen analysis was also possible due to moderately well preserved pollen grains.

There appears to have been a continued wooded presence at Cleddon Bog, initially with the presence of a diverse woodland composed of *Alnus*, *Betula*, *Pinus*, *Quercus*, *Ulmus* and *Corylus*. Between 3000 and 50 years BP arboreal dominance of the pollen diagram decreases significantly and an opening of the woodland appears to occur, with large amounts of Poaceae, Cyperaceae and *Calluna vulgaris*. Wooded species then increase slightly in the recent past. The continuity woodland at the site is likely to have resulted in the present high species diversity of the bog. The record for Cleddon Bog also includes a detailed charcoal record, sampled continuously throughout the core and classified into three size classes. This record reveals a local fire record, with macrocharcoal being recorded in high amounts at two points in the diagram relating to vegetation change.

The linkage of burning within the landscape and vegetation was further investigated by the development of the British Isles Charcoal Database (BICD). The database holds a significant number of charcoal records for the British Isles. The compilation of this database is significant, as there is no known existing database of charcoal records from the British Isles. Mapping of these records has enabled an assessment of the spatio-temporal relationships throughout the Holocene. Results of this spatio-temporal assessment indicates that fire has been present throughout the Holocene across the British Isles at varying intensities. In the early Holocene charcoal values appear to have been low, with climatic conditions likely to be the controlling factor, particularly as a result of unfavourable growing conditions and therefore lack of fuel. Mid-Holocene charcoal records are variable and these changes in charcoal abundance appears to correlate with changing climatic conditions, particularly with wet shifts, increasing fuel moisture and therefore partially inhibiting ignition. The late-Holocene record shows a steady increase in charcoal abundance within the record particularly in upland areas, most likely attributed to increasing management of the landscape by humans. The record then appears to show fire suppression of fire within the landscape. Pollen-charcoal relationships support a correlation between burning and *Calluna vulgaris*, suggesting a strong relationship between British heath- and moor-lands and fire. Negative correlations between *Betula* and *Salix* and charcoal values suggest limited fire in the wooded environment.

6.2 Future Work

This study has attempted to use a selection of techniques to investigate the disturbance mechanisms present within sites in the British Isles and detail the vegetation history of specific sites. To develop this research further work is needed.

Further stand-scale palynological analysis within the British Isles at sites of specific interest for conservation. Although these sites can be difficult to locate, continued communication between site managers and academics prove fruitful. Additional studies could continue to provide a useful tool for the management of these sites. It could also provide us with detailed information regarding disturbance mechanisms active at a variety of location, thus informing debates on hypotheses such as the wood pasture hypothesis and the high forest hypothesis. More detailed historical research for selected sites would provide additional context to the finding of palynological studies. Information could include landuse during specific time periods.

Additional collation of past, obscure and unpublished charcoal records to the British Isles Charcoal Database, along with the continuous updates of recent publications will strengthen the conclusions drawn from this initial study. Additional sites have been identified and are to be added to the European Charcoal Database at a later date. Further information included could be the use of detailed climate data for the Holocene, which could then be analysed in conjunction with the charcoal record, potentially providing more information to identify the main drivers of fire during different time periods. Further spatio-temporal study could be to look at regional differences in the Holocene fire regime, may be dictated by anthropogenic activity or by other variables such as precipitation. The correlation of estimates of grazing within the British Isles could also be an interesting development, especially with the apparent presence of an additional axis in the Detrended Correspondence Analysis of pollen-charcoal relationships.