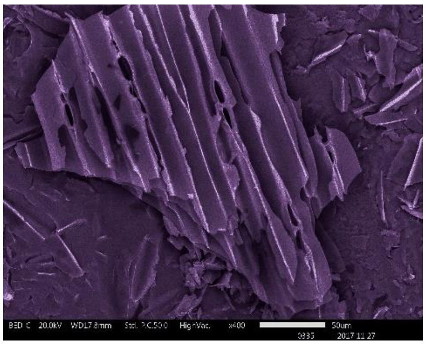
PhD Thesis

Image analysis of charcoal fragments to explore Holocene fire – vegetation dynamics in Northern Europe



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

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Declaration

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

Signed Kre Haball

Dated 19 May 2019

Abstract

Many sedimentary deposits are vital archives of fire-vegetation-climate records. Developing a better understanding of these relationships has relevance to understanding the impact of changes in climatic conditions, such as the increase in summer temperatures that is forecast for the next fifty years and beyond. Charcoal fragments can be used as a proxy for fire events however there is no standard method for their isolation from sediments or standard quantification unit. Many of the fire histories for the U.K. focus on a narrow temporal range and use a variety of quantification units to overcome methodological difficulties in comparing and compiling records. Statistical techniques can be employed to compile records; however, this leads to a reduction in the sensitivity of the data in detecting low impact disturbances such as ground fire and the light impact of early Mesolithic tribes. For this thesis, an image analysis method has been devised and robustly tested through analysis of macrocharcoal fragments. This method is initially used to explore the fire-vegetation-climate history of an upland ombrotrophic bog, Robinsons Moss, Peak District, U.K. in a multiproxy study covering the last 8200 years. The analysis is then extended to determine the local fire history for upland sites in and around the Peak District region using the Landscape Reconstruction Algorithm devised by Sugita (2007 a, b) in an empirical data-driven approach that does not require data transformation of charcoal records and the subsequent loss of sensitivity in the results. Four sites in northern Europe are used to explore the wider spatial fire- vegetation-climate relationships. This is achieved by using the new method for charcoal fragment analysis combined with the quantitative fire – vegetation response technique, redundancy analysis.

Results show that the percentage of the variance in the vegetation dynamics explained by fire for sites within the Peak District and also for the sites in Denmark, Germany and Sweden does not exceed 30% for the last 13,500 years. Although fire is not the dominant driver at the sites explored in this thesis, it does have a substantial impact on the vegetation dynamics and soil chemistry. The results from this research implies that climate is more likely to have long-term control over vegetation dynamics at these sites.

Acknowledgements

I would like to thank my main supervisor, Professor Richard Bradshaw and second supervisor Dr. Fabienne Marret-Davies for giving me the opportunity to study paleoecology at the University of Liverpool and for their support, encouragement and friendship over the last seven years. Richard widened my research experience by giving me the opportunity to contribute to the European projects included in this thesis. Richard also provided funding from the FIREMAN BiodivERsA project allowing me to work as a research assistant and also contributed funding for the first three years of this project. My research experience was greatly enhanced through the encouragement of both Richard and Fabienne to attend workshops, to present papers at conferences and I was able to be part of a variety of national and international experiences including a day with Maggie Aderin Pocock learning about scientific presentations and a palaeoecological tour of western Ireland. I also received a bursary for a four month stay at Lund University, Sweden from the Erasmus study abroad exchange programme.

I would like to thank Mikael Ohlson for his support and patience in completing our paper 'Fossil charcoal quantification using manual and image analysis approaches' and also to my co-authors Lee Bradley and Mette Overballe-Petersen for including me on their papers. Thank you also to Chiara Molinari and Veiko Lehsten for the opportunity to work on their project within the Jamtgaveln Nature Reserve. For the last two years, I have worked as part of a project based in the Czech Republic with team members that included Jen Clear, Petr Kuneš, Niina Kuosmanen and Vachel Carter. I would also like to thank Gina Hannon for the opportunity to work on several of her very interesting conservation projects in Sweden and Denmark and the opportunity to contribute to the Sällstorpssjön paper.

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I have also benefitted from the support of family and friends outside of university life for which I am truly grateful. Without their help, completing this PhD thesis would have been impossible. My very good friend John has given me immeasurable support over the last seven years. Thanks is a small word that does not reflect the huge encouragement, positivity and support given that has helped me in so many ways. Thanks also to Fiona Ford who encouraged me to take the first leap back into education in 2008. My son Alex has also been encouraging and supportive particularly over the final months with his advice to ‘just finish it!’

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Chapter 1 Introduction

1.1 Abstract

Beneath many upland U.K. peat landscapes lies the temporal and spatial archive for Holocene environments laid down over thousands of years across Northern Europe in a wet, oceanic climate. Reconstructing past environmental conditions using peat, lacustrine and forest hollow sediments, can provide evidence for changes in vegetation dynamics and the dominance of a range of ecosystem drivers across sedimentary landscapes throughout the Holocene. Drivers such as fire, vegetation succession and major disturbances can be inferred using appropriate palaeoecological indicators. There are inherent difficulties in untangling drivers of the complex network of dynamic environmental conditions and feedback mechanisms that can be reconstructed from Holocene sediments. This thesis presents a detailed methodology used to explore Holocene fire – vegetation-climate relationships across northern Europe.

These relationships are used to determine how and why charcoal fragment abundance varies during the Holocene. Many sediment archives of fire regimes already exist however, there is no standardised method for isolating and quantifying charcoal fragments and statistical data transformation reduces data sensitivity. Here, a new method using image analysis is devised and tested. Data from European sites is then analysed using a quantitative fire-vegetation response technique, redundancy analysis. The combination of these two aspects of this thesis creates a new approach to the analysis of fire-vegetation-climate relationships that can be used with any Holocene sediment. With this novel approach using non-transformed data, the results show a consistency in the dominant driver for the sites from the Peak District and for the sites in Europe.

1.2 Research questions

The questions central to this project are: -

A. Can a semi-automated image analysis system generate a reliable estimate of charcoal frequencies in sediments?
B. How does the Holocene fire regime at Robinsons Moss, Peak District compare with the regional fire regime across the Peak District?
C. How important has Holocene fire been as a driver of vegetation dynamics in northern Europe?

1.3 Thesis Aims and Objectives

Aims

This research project aims to investigate the methodology of using charcoal fragments to represent fire events, and hence fire regimes, within Holocene paleo-environmental reconstructions across northern England and northern Europe. To achieve this a new robust methodology is presented as a standard method for the isolation, processing and quantification of macroscopic charcoal fragments. This method will then be tested on sedimentary cores extracted from several sites representing local, regional and continent wide charcoal particle source areas. The results will be discussed in context with developing a greater understanding of Holocene fire-vegetation – climate relationships.

Objectives

1 Produce high resolution, well dated multiproxy data from sedimentary deposits found within an ombrotrophic upland peat bog site using palynology, charcoal fragment and Non Pollen Palynomorph analysis to investigate Holocene fire-vegetation-climate relationships.

2 Devise a quick robust method for isolating and quantifying charcoal fragments using image analysis and compare this with a different well known method; quantification by mass.

3 Test the use of this method at different sites across N. Europe by processing and analysing charcoal fragments from peatbogs, forest hollows and lake sediments and to test the limitations of the method under these different transport and deposition routes.

5 Use the landscape reconstruction algorithm devised by Sugita (2007a, b) to reconstruct regional and local pollen proportions by applying the LOVE and REVEAL models at sites in

and around the Peak District, U.K. Compile regional pollen proportions using the REVEAL model (Sugita, 2007a) for key taxa and compare this with the local pollen proportions for the various sites using the LOVE model (Sugita, 2007b).

6. Use vegetation response analysis to compare microcharcoal records for sites in northern England and compare macrocharcoal records for sites in northern Europe.

1.4 Thesis structure

This thesis comprises eight chapters that include two papers both published in The Holocene an international peer-reviewed journal (Chapters four and seven).

Chapter 1 Outlines the content of each chapter, provides an overview of the thesis and states the aims, objectives and research questions.

Chapter 2 Outlines the concepts and provides background information for the research areas that were investigated in this thesis.

Chapter 3 Describes a new robust, fast method of high resolution macrocharcoal isolation with quantification using image analysis of fragments.

Chapter 4 Is a published paper that compares two different methods for the isolation of charcoal fragments; measurement by mass and measurement by area.

Halsall KM, Ellingsen VM, Asplund J, Richard Bradshaw and Ohlson, M.; Fossil charcoal quantification using manual and image analysis approaches. The Holocene (2018) Vol 28(8) 1345 – 1353 (Chapter 4 p149 – 178)

Author contribution

Halsall K.M.	Main author responsible for data processing (half of samples) and collating using image analysis, data interpretation, images of Liverpool samples, writing half of the manuscript, manuscript submission.
Vanessa M.E.	Data processing (Norwegian samples), collating and contributed to interpretation of data.
Asplund, J.	Statistical analysis, figure production and image of Norwegian samples.

Olhson, M	Responsible for half of the manuscript writing and review of manuscript.
Bradshaw, R.H.W.	Manuscript review.

Chapter 5 Describes a multiproxy study of Robinsons Moss, Peak District, U.K. and investigates the fire history using a variety of statistical methods

Chapter 6 Expands the data for Robinsons Moss by including data sets from the Peak District region and beyond. Statistical analysis of data to examine the fire-vegetation relationships.

Chapter 7 Is a published paper using the image analysis method for charcoal fragment analysis with redundancy analysis to describe the fire-vegetation relationship from Sällstorpjon, Halland, Sweden.

Hannon GE, Halsall K, Molinari C, Boyle, J., Bradshaw, R.H.W. (2018) The reconstruction of past forest dynamics over the last 13,500 years in SW Sweden. The Holocene, 1-10. (Chapter 7 pp 178 – 194)

Author contribution

Hannon G.E	Main author responsible for data collection, data processing, analysis, interpretation and manuscript preparation.
Halsall, K.M.	Responsible for processing and quantification of charcoal record, fire-vegetation response analysis and interpretation.
Molinari, C.	Responsible for processing of charcoal data using CharAnalysis programme.
Bradshaw, R.H.W.	Manuscript review.

Chapter 8 Uses a quantification technique (Redundancy Analysis) to compare the impact of Holocene fire on vegetation dynamics at four sites in Europe.

Chapter 9 Further work

Annex1 Additional data and graphs

Annex 2 Further papers

1.5 Author overall contributions

The author was present and assisted with the field work for the Robinsons Moss core, with Richard Bradshaw and Tim Shaw in June 2009.The author dissected and sub sampled the core, selected and prepared samples for radiocarbon dating, palynology, charcoal fragment analysis and Non Pollen Palynomorph (NPP) analysis. The author isolated and quantified charcoal fragments from Robinsons Moss using the image analysis method developed as part of this project. The author also processed and used the image analysis method to analyse sub samples from cores taken from Sällstorpssjön, SW Sweden; Gribskov, Denmark; Carlshof, Germany, and five cores from Jamtgaveln, Norway.

All statistical work in R was completed by the author. The R scripts for 3D plotting and fire-vegetation analysis and redundancy analysis (RDA) were given to the author by Danielle Colombaroli as part of his paleofires course, Royal Holloway, University of London. The maps were created using ArcGIS with assistance from Tinho da Cruz. Pollen proportions were calculated by the author using the LRA model developed by Shinya Sugita (University of Tallinn, Estonia) with initial assistance by Anna Birgitte Nielsen (Lund University, Sweden) as part of the paleoecology master's Course, 2016 at Lund University and Petr Kuneš (Charles University, Prague). The LRA runs were completed by the author. The CharAnalysis results were compiled by the author with initial assistance from Vachel Carter during a knowledge exchange session at Charles University, Prague, 2018.

The author was responsible for all figure preparation and data analysis apart from some of the figures and tables in the published papers.

Manuscript preparation was the responsibility of the author with useful comments from Professor Richard Bradshaw and Dr Fabienne Marret-Davies.

1.6 Thesis summary

Fire is a natural element of many ecosystems worldwide. Within Holocene sediments, lies the evidence for changes in fire-vegetation-climate dynamics. Sedimentary peat laid down over thousands of years across northern and central Europe can be used to reconstruct natural and cultural heritage using a variety of botanicals as proxies for environmental conditions. Peat deposits that are open areas of bog, heath and grassland or within forested areas are vital resources that encompass six vegetative communities in the EC

Habitats Directive [92/43/EEC] for Britain and Ireland (Thompson *et al*, 1995, JNCC and Defra, 2010) that are protected under many national and international agreements for water supply, socio-economic resources, conservation, biodiversity and recreational needs. Peat is also a significant global carbon storage sediment (Marrs *et al*, 2018). Summer temperatures and precipitation regimes for upland peat habitats are forecast to change over the next fifty years (IPCC, 2017). It is important to continue research into how past environmental conditions led to the type of landscapes we see today such as improving Global Climate Models (GCMs), understanding local and regional historic climatic and vegetation mechanisms and gaining further knowledge of the impact of early human activity in opening up forested landscapes and grazing herbivores with other disturbances. This type of research can provide vital information that could improve the ability of stakeholders to mitigate against the probable increase in wildfires. This information is vital if we are to develop our understanding of vegetation response to future increase in temperature in particular with reference to fire events and ecosystem management.

There are many indications of *late* Holocene human activity impacting on moorland vegetation dynamics viz: prescribed burning, grazing and grouse breeding (Marrs *et al*, 2018; Davies, 2016) but fewer indications of the *long* term impact of anthropogenic disturbances and changes in climatic condition. Evidence suggests that Mesolithic tribes ranged across the Peak District (Preston, 2012; Preston *et al,* 2018). An earlier study by Switsur and Jacobi (1979) found Mesolithic flint 'industrial sites' radiocarbon dated at 6,620 +/-110 years. BC. Artefacts and tools such as flints and microliths have been found scattered across the Peak District. This evidence is contemporary with studies of the previous marshland known as Doggerland, now under the North Sea, which now separates Britain from other European countries such as Germany, Denmark, Sweden and Norway (Coles, 2000). Between 5800 and 6000 years BP the rising sea level finally led to a breach between the North Sea and Channel drainage system cutting the U.K. from northern and continental Europe. As the sea level rose, the coastal and inland people living in Doggerland would have migrated into either the U.K. or other neighbouring countries along with animals such as horse and red deer (Coles, 2000). Other studies in the U.K have explored Mesolithic impact on early/mid Holocene forest disturbance (Simmons *et al*, 1996: Mighall *et al*, 2008; Davies *et al*, 2016) and found evidence of complex interactions between drivers during this time period. More recent regime shifts thought to be caused by human activity have been identified such as that from heath to grass during the last millennia (Davies *et al*, 2016). Research in the Peak District is also currently focussed on conservation, pollution and peat restoration by *Sphagnum* introduction (Shuttleworth, *et al* 2014; Dixon *et al*, 2014). Linking modern and paleoecology is needed if we are to increase our depth of knowledge regarding the long term trends that earlier disturbances such as human activity could have contributed to modern vegetation dynamics. Although separating natural burning from anthropogenic activity is obviously extremely difficult, detecting temporal and spatial patterns could improve our knowledge of these different ignition mechanisms.

Robinsons Moss, Peak District, owned by United Utilities but with open access, was chosen for this study as it is a good example of an ombrotrophic peat bog that is relatively undamaged. There are some signs of erosion that has left peat hags and gullies around the edge of the peat bog. Restoration work is visible for these areas of the mire system. The central basin is relatively undamaged with a visibly high water-table. The presence of *Sphagnum* moss indicates current peat growth and a pool and hummock system is still in place. The peat bogs surrounding Robinsons Moss have been extensively studied by John Tallis (1965 – 2000) and colleagues. The original pollen data compiled by Tallis that covered 4000 BP – present day for Robinsons Moss are not available, although the early work covering 9000 – 4000 years BP is published (Tallis, 1987, 1990). A composite pollen-charcoal record for a nearby site, Featherbed Moss (Tallis, 1973) is also published however this only covers 5500 to 370 years BP. A new record of charcoal fragments (macroscopic and microscopic), pollen grains, spores and non-pollen palynomorphs and geochemistry for the last 8200 Cal years BP has been compiled as part of this study. The method of analysis for charcoal fragments (as a proxy for fire events) uses image analysis so a detailed study of individual fragments has been completed. The fire record has then been explored by comparison with data from the other proxies, such as pollen, fungal spores and with results from geochemistry and Near Infra Red Spectroscopy (NIRS). Humification values were calculated using an end-member technique in NIRS analysis developed at the University of Liverpool that has provided information on the hydrology of the lower section of the core extracted from Robinsons Moss. Hydrology is an important driver of change for mire systems and is directly linked with precipitation and hence climatic conditions (Ellis & Tallis, 2001). Quantification values (ppm) for elements within peat were calculated using XRF analysis.

The data from Robinsons Moss are then compared with sites in the Peak district and also with sites in northern Europe.

Justification:-

1. Peat is an excellent archive of fire histories and other disturbances that impact on fire prone ecosystems. Peat accumulates linearly and minimum sediment mixing is an advantage over the use of lacustrine sediments.

2. Ombrotrophic bogs are particularly useful in the study of fire histories as their hydrology is linked with precipitation and temperature.

3. Lags in vegetation response make it difficult to untangle drivers of environmental changes, however long-term studies using for example cross-correlation and vegetation response analysis can separate the different drivers that operate at different time periods and over different time series.

4. Fire events are a major historic factor present within many ecosystems globally. Changes to fire regimes can have a direct impact on vegetation dynamics. Changes in climatic conditions can change biomass availability and hence fire regimes. Fire regimes can be linked to the presence of human activity (care needs to be taken as other disturbances such as wind throw and deforestation can be erroneously correlated with fire events). Analysis of the parameters of a fire regime such as fire return interval and fire frequency (number of fires per 1000 years) can indicate possible differences between natural fire and anthropogenic activity as cause of fire ignition (Clear, 2015; Kuosmanen, 2016). Light impact Mesolithic human activity can be difficult to detect in palaeoecological records however several studies in peat moors across Great Britain are published where human activity has been shown to be responsible for early changes in vegetation dynamics during early and middle Holocene (Fyfe *et al*, 2018; Innes, 2010; Innes, 2013; Albert, 2015; Payton, 2016; Griffiths, 2017). Other papers question whether these signals are caused by human activity (Jacobi, 1976; Tipping, 1995; Brown, 1997; Ryan & Blackford, 2010; Edwards & Whittington, 2000). In order to understand and see links between fire – vegetation dynamics – climate and people it is important to have long-term research where these links can be more easily detected and untangled. However, to understand these relationships, it is necessary to explore the possible ways and the extent to which early humans may have impacted on the region being studied. This is complicated by the natural openness that can be present in a forested area. This has been explored in the Vera debate (Vera, 2000). Archaeological evidence for the presence of Mesolithic tribes exploiting resources within the Peak District is discussed in chapters five and six.

5. There is no standard methodology for analysis of charcoal fragments which can lead to a loss of sensitivity when records are compared. This study has devised a new methodology that has been tested on cores from across northern Europe. The results have been analysed using robust statistical methods.

6. Multiproxy studies that include e.g. Non Pollen Palynomorphs (NPPs) and geochemistry, can provide more detailed information that can explore links between fire events and changes in vegetation dynamics. NPPs can also provide information on hydrology, forest, rotting trees, presence of grazing animals (coprophilous fungi). These issues are discussed in chapter four as part of the records for Robinsons Moss.

Testate amoebae were investigated as a possible proxy for hydrological changes, however a sufficient abundance of testate amoebae was not found in the peat samples from Robinsons Moss, so this line of research was discontinued. Testate amoebae records and transfer functions have been successfully analysed for changes in hydrology at other sites in the north of England (Blundell, 2005; Hughes, 2000; Chiverrell, 2001) and have also been analysed alongside other hydrological proxy records. These have been found to have limited correlation when examined in detail for dating of wet/dry shifts A wider range of dating can lead to some correlation in the data (Schulting, 2010). Climate records for the N hemisphere from ice cores such as NGRIP and Vostock are not usually sensitive enough to be useful in regional studies. Climate records from the fossil remains of chironomids can be useful if available such as Langdon (2004) using Talkin Tarn, Cumbria which records temperatures from 6000 years BP. Pollen assemblages can indicate general temperature changes although these will have a 100 – 150 year lag in the record depending on the life span of the trees. Cold climate trees percentages compared with temperate tree percentages can indicate changes in climate. However, it is important to use climate data that is independent of the palynology to avoid circular arguments.

7. Studies that explore fire – vegetation- climate relationships are still needed if we are to mitigate for the forecast increase in summer temperatures that could lead to an increase in wildfires. The data could also provide information that could be useful for management plans. Identifying environmental changes, including climatic conditions during the Holocene can be conducted successfully using peat profiles. In particular, ombrotrophic bogs, which are only water fed through precipitation, are useful indicators of changes in hydrology which are linked to climatic conditions, although as stated above it is important to use independent climate records.

Chapter 2 Concepts and Background

The overriding aim of paleo-environmental studies is to deepen our understanding of the longer-term processes and interactions that operate within the Earth system and of the ways in which they change through time, ‘concentrating on those aspects of past environmental change that most affect our ability to understand, predict and respond to future environmental change’

(Alverson and Oldfield, 2000).

Fires became widespread across Earth towards the end of the Devonian era around 350 million years ago during the time of spreading forests. The earliest evidence for charred plant fragments has been found from a much earlier time period during the Late Silurian, when oxygen levels were above the present atmospheric level of 21%. During the Triassic, Jurassic and Cretaceous, oxygen levels fluctuated but remained high. Towards the end of the Cretaceous period, around 100 million years ago, flowering plants diversified and expanded. Small charcoalified fossil flowers and woods from around the globe have been found dating from around 70 million years ago during this time of high fire which may have aided the evolution and spread of the earliest flowering plants, the angiosperms (Bond & Scott, 2010). Since this time, fire has been an integral disturbance agent in most ecosystems (Bond *et al*, 2005; Colombaroli *et al*, 2010) affecting ecosystem structure, vegetation dynamics and climatic feedback systems (Pyne *et al*, 1997). Considering the long length of time that fire has been part of ecosystems, it is not surprising that many plants in fire prone ecosystems have developed strategies to cope with the repeated occurrence of fire events. For example, lignin present in bark evolved as a mechanism to survive fire through resistance to burning; some angiosperms evolved to produce seeds that only germinate after a fire ((Buhk & Hensen, 2006; Pausas, 2015; Lamont, 2019). These are only two examples out of many more strategies that evolved throughout the millions of years since the expansion of angiosperms. For more recent millennia, during the last 10,000 years of the Holocene, fire events are commonly described as being of either natural or anthropogenic in origin (Carter, 2018). The addition of human influence on fire regimes complicates fire-vegetation-climate relationships. Separating ignition sources is difficult, as is untangling these complex relationships that involve positive and negative feedback mechanisms, lag effects and long and short-term trends (Bond *et* al, 2005; Conedera *et al*, 2009; Whitlock *et al*, 2010).

Developing our understanding of why Holocene fire regimes change, requires an understanding of the long history that plants have with fire, the adaptations of individual plants and plant communities to fire, spatial and temporal climatic trends as well as the inclusion of archaeological evidence (where available). Other parameters that affect fire regimes include differences in topography, soil types and soil development. Relationships between these parameters are often non-linear and complex.

The analysis of Holocene lacustrine and peat sedimentary deposits (Whitlock & Larson, 2001) and forest hollows (Clear *et al*, 2013) can provide detailed information about these relationships, although each of these types of deposits have limitations as well as advantages in the reconstruction of fire regimes. For example, peat sediment has the advantage over lacustrine sediments in that charcoal fragments, used as a proxy for fire events, are not subject to mixing and redeposition as they are in lakes (Conedera *et al*, 2009). Bogs are thought to provide a more local reconstruction of fire events than lakes (Conedera *et al*, 2009; Mooney & Tinner, 2011; Feurdean *et al* 2012) however peat sediments can be more difficult to accurately date due to the incursion of roots and plants from younger sediments into older sediments.

Fire regimes vary spatially and temporally (Power *et al,* 2008; Vanniere, 2011; Marlon *et al*, 2016). Combining fire records is a useful mechanism to determine ecosystem drivers of biomass burning across larger regions but this tends to mask any spatial variability in fire regimes due to differences in local conditions (Blarquez *et al*, 2015). When using one site, local conditions become significant (Gavin *et al*, 2006; Whitlock *et al*, 2010). Cui *et al* (2014) showed that one site is representative of fire history as several cores from same site showed comparable trends. Studying local conditions through the use of a single site, is particularly important for sites at higher altitudes where summer temperatures are predicted to increase which could increase the probability of wildfire occurrence (Gallego-Sala *et al*, 2016). Recreating local fire events can depend on the chosen methodology particularly with regard to the size of particles. There is debate as to the distance travelled by different sizes of charcoal fragments although often these studies refer to the use of lacustrine sediments rather than peat sediments. Particle motion theory was used by Clark (1988) to show the different taphonomy of particles travelling in air columns and found that larger particles would travel shorter distances as they are less likely to be drawn into thermal air columns, however larger charcoal particles moving by water tend to float more readily than smaller particles and will therefore travel further (Scott, 2010). Some studies indicate that larger fragments represent more local fire events and smaller particles particularly those found on pollen slides represent regional fires (Whitlock & Larson, 2001). Carcaillet *et al* (2001) showed that analysis of smaller charcoal fragments found on pollen slides, even if subject to fragmentation during transport and processing, still only represents about 50% of the peak values of macroscopic charcoal found in the same core. Large pollen slide charcoal fragments are often thought to represent the same fire source area as macrocharcoal fragments. Florescu *et al* (2018) found that in the Carpathian Mountains, Romania, lakes provide a higher charcoal influx than bogs and that accumulation of macrocharcoal sediments in lakes was subject to different processes than those in bogs. Adolf *et al* (2017) showed that microcharcoal and macrocharcoal can represent the same regional fire record using lacustrine sediments. This research shows some of the difficulties in achieving methodological and interpretive consistencies between fire records. Obtaining significant results can depend on the volume of sample used in the analysis as very small subsamples (<2 cm^3) can lead to inaccurate temporal interpretation due to the variation in fragment abundance across a site and therefore not able to represent a robust fire history (Cui *et al*, 2014). Carcaillet *et al* (2001) suggests that 3 cm^3 sediment should be used to recreate fire regimes to minimise variation within a site, however Adolf *et al* (2017) suggested 10 – 12 cm^3 was a useful volume.

2.1 Why is historic fire research important?

A special IPPC report (2018) states that global warming is likely to reach 1.5^0 C above pre-industrial levels between 2030 and 2052. (https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf). This could have dramatic consequences for peat habitats such as the Peak District. These fire prone habitats ae likely to see a rise in fire events under this scenario. Peat can accumulate in (sometimes) deep deposits, as in Robinsons Moss, Peak District where at least 5 m in depth has been laid down during the Holocene. Globally peatlands cover around 4.16 x 10^6 Km^2 or about 3% of the globe's total land area and contain around 400 – 600 Pg. Carbon (Rydin and Jeglum 2006; Tarnocai, 2006; Page *et al*, 2016; Wang *et al*. 2009). Climate projections for upland peat areas suggest that weather conditions will become milder with warmer, wetter winters and hotter, drier summers (Jenkins, 2009). With drier conditions and/or increased drainage, this is likely to increase fire intensity and frequency on peatlands (Frolking, 2011). Under this scenario, there could be a higher likelihood of wildfires occurring on these open peat environments, changing these historic carbon sinks into a source of atmospheric CO_2 (Worrall *et al*, 2009; Albertson, 2010). This would impact on the environmental and socio-economic services provided by regions such as the Peak District and is likely to trigger biotic reorganisation with broad consequences for land-surface feedbacks and the global carbon flux (Flannigan *et al*, 2009).

Long-term studies can provide detailed information on the drivers of environmental dynamics over past millennia that could be useful for management plans that aim to mitigate for changes in climatic conditions. Projects that link modern ecology and paleoecology could be a useful approach that provides the greatest range of information for fire prone ecosystems. Prescribed fire is a current and historic management strategy for peatlands in the Peak District (Davies *et al*, 2016; Marrs *et al*, 2018) and also for example in the western U.S.A. forests (Westlind *et al*, 2017). In the Peak District it is currently a highly contentious strategy due to ongoing debates regarding socio-economic, conservation, biodiversity and water resource management plans. These issues could also be relevant for other peat moorland in the U.K. A recent paper by Marrs *et al* (2018) discusses the impact of prescribed burning at Moor House, Upper Teesdale and concludes that zero prescribed burns can lead to unwanted building of fuel load and that the length of the fire return interval impacts on biodiversity. Maximising biodiversity whilst maintaining environmental services is a difficult balance and can be a source of conflict between stakeholders in such landscapes across the UK. Mitigating changes in climatic and environmental conditions is a current and important task for stakeholders. Although conservation often aims to maintain and/or regain past levels of biodiversity, we can never truly recreate historic landscapes as environments are dynamic and there will always be a difference in paleo-environmental conditions from present conditions. There are often successional changes and vegetation assemblages that are unique to past environments and that cannot be reconstructed. However, we can increase our understanding of the development of contemporary environments and the interaction of human activity as part of the long-term relationship of the fauna and flora of these habitats and hopefully learn to appreciate their role in our lives and the role that our current actions will have on natural environments and our own future.

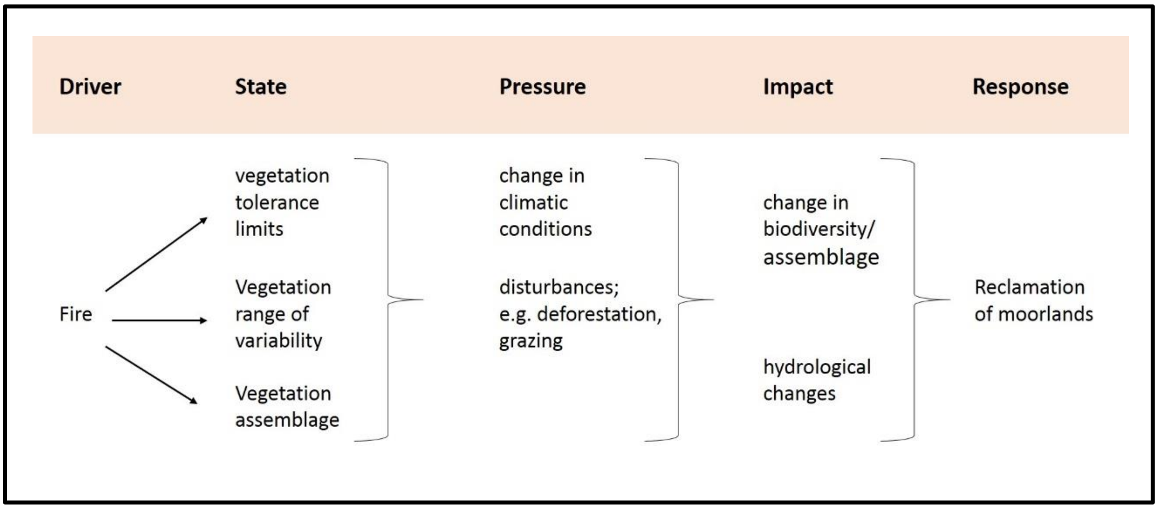


Table 2-1: Devised by Karen Halsall using concepts within Oldfield (2014) to highlight the interaction between natural processes and disturbances that can lead to intervention to mitigate loss of biodiversity.

This study aims to investigate the relationship of fire with vegetation and climate in fire prone ecosystems such as Robinsons Moss and at other sites across Northern Europe. Understanding a deeper history of the fire – vegetation – climate relationships, as this thesis attempts to accomplish, is an important way to add information to this ongoing debate.

2.2 Fire ecology

Since early work by (Swain, 1973; Payne, 1996; Clark, 1982), charcoal fragments found in sedimentary deposits have been used to interpret fire histories. Understanding fire ecology requires knowledge of ecosystem dynamics, mechanisms and feedback systems as fire has a complex relationship with vegetation dynamics and climatic conditions (Bowman, 2009, 2011). Global fire can be seen on composite satellite images (figure 2-1). Major fire locations are related to seasonal orbital forcing, lightning strikes and also fire setting by people particularly in the savannah, forested ecosystems and in the tropics. It is in these regions where most current burning takes place.

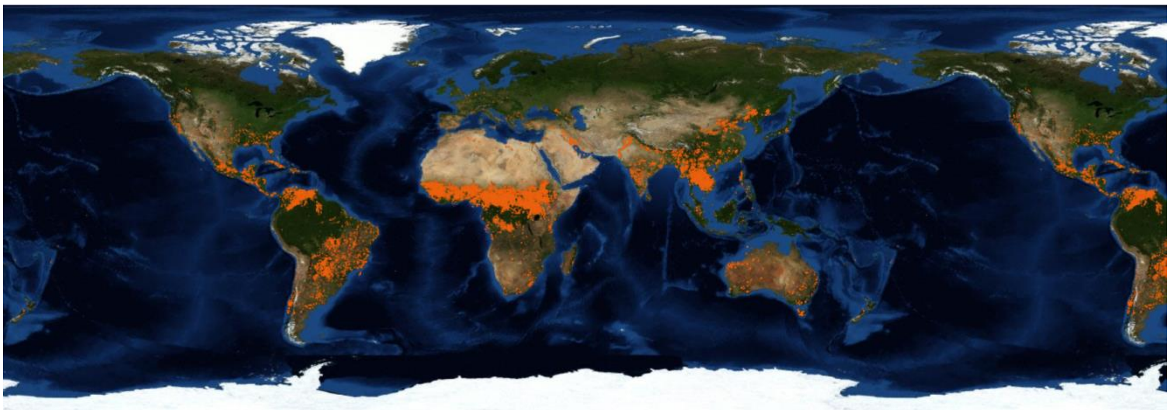


Figure 2-1 Remotely sensed location of fire between 29th January and 5th February 2019, detected by Modis (NASA, 2019-02-05).

Source: https://firms.modaps.eosdis.nasa.gov/map/

In their book, Bradshaw and Sykes (2014) state 'fire is a perfectly natural, episodic disturbance agency of many ecosystems but has been exploited by people for so long that its natural status is often hard to determine'. In a world without fire, modelling runs show that Brazilian and African savannahs would be replaced by forest and that global forests would expand to at least double their current size (paleofire course, Holloway University of London, February 2018). This highlights the complex nature of Holocene fire-vegetation-climate relationships where inherent natural cycles with temporal and spatial patterns of disturbance interact to create fire regimes that can then be recreated in paleoecology studies. Disturbance events such as wind throw, flooding, drought and fire can be both intrinsic to the ecosystem and events caused by disturbance to natural cycles. Disentangling these cycles and disturbances is difficult and whilst general trends are known, details of the relationships are still poorly understood.

An important aspect of fire ecology and the reason why long-term studies are important is the development of fire adapted, fire resistant or fire tolerant taxa within an ecosystem. Fire disturbance events can lead to an altered successional route and can affect species composition at short (annual) and long (centennial) time scales (Tinner, 1998). For example, if a fire adapted pioneer species regenerates first after a fire event and becomes dominant such as *Pinus sylvestris*, or *Abies alba*, this could push the stable state in which fire events were previously low, due to the dominance of fire resistant species, across an ecosystem threshold and lead to an increase in fire events.

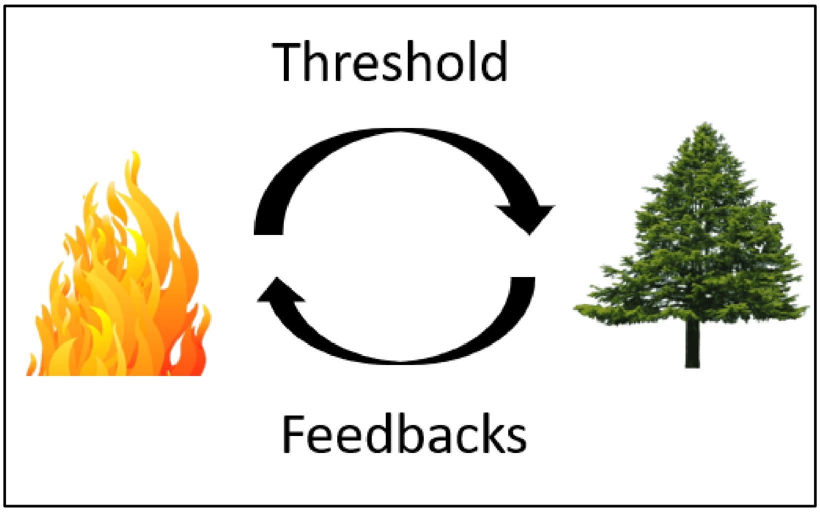


Figure 2-2 showing a basic conceptualisation of the relationship between plant threshold and dynamic vegetation feedback mechanisms.

Figure 2-2 conceptualises the impact that fire adapted taxa or fire tolerant species can have within an ecosystem. Change in the dominance of fire adapted or fire tolerant species can cause a regime shift (through feedback mechanisms) to an ecosystem where fire events increase or decrease respectively. In the Swiss Alps, Holocene fire affected ecosystem properties by promoting fire-resistant pioneer species at the expense of fire sensitive late-successional species (Tinner *et al*, 2000; Colombaroli *et al*, 2007). For sites at which some taxa are surviving at their tolerance limits, such as an altitudinal treeline, quite subtle changes in compositional and structural changes can be seen more easily than at other less sensitive sites. Fire regimes studies at such sites can be important in revealing previously unknown palaeoecological information such as in the study by Tinner & Theurillat (2003) in the Swiss Alps where the treeline ecotone was found to be 200 m above that previously thought. To understand the impact of fire on ecosystem components, the long-term vegetation response to fire as well as the role of fire in net primary productivity and nutrient recycling should be investigated further (Colombaroli & Tinner, 2013).

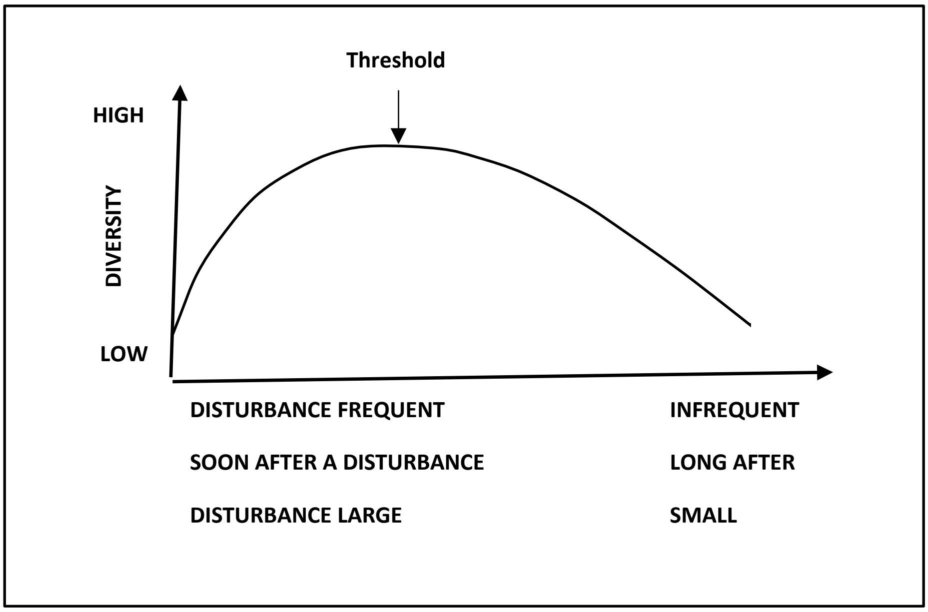


Figure 2-3 Redrawn from Pickett & White (1985) showing the Intermediate Disturbance Hypothesis where diversity is thought to be highest at intermediate disturbance quantity, time and magnitude (Connell, 1978).

Understanding the impact of disturbances on an ecosystem is an important concept for conservation organisations as it provides information about when a species is reaching a threshold after which the ecosystem community could change to a different state, stable or otherwise (figure 2-3). Hence it can also be relevant to understanding the fire ecology of an ecosystem to look for gradual changes or sharp transitions in the ecosystem. Fire is only one of several disturbance factors that can influence an ecosystem, for example wind throw, droughts, floods or grazing pressure, and it is important to not confuse these signals in the vegetation dynamics. Disturbances in ecosystems do not always have a negative effect on ecosystems; they can lead to an increase in plant biodiversity; however this can decline when disturbances are absent or too severe (Connell, 1978).

Table 2-1 was devised to show that a strategic approach to the management of fire prone ecosystems can be assisted by long-term palaeoecological studies which can reveal the interconnectedness of drivers and disturbances.

2.3 History of fire

Around 370 million year ago, global oxygen levels increased sharply and with it, the expansion of forest fires. Since then, oxygen levels are thought to have mostly remained above the present level of 21% (below 15%, wildfires will not usually occur) so it is fuel load and ignition source that remain the dynamic variables (Scott *et al*, 2000; Scott,2018). The first evidence for fire has been found in Silurian sediments however since the expansion of angiosperms around 130 million years ago, we have lived in a high fire, high oxygen world (Scott, 2000, 2006). The earliest evidence for domestic fire is thought to be the one million year old bones found in Wonderwerk Caves, South Africa (Berna, 2012), although cooked food may have appeared around 1.5 – 2 million years ago. The use of fire probably facilitated the spread of humans into colder regions (Gowlett, 2013; Parfitt, 2010) and as human population expanded and variously collapsed across the globe, evidence for the use of fire by humans has been found in most biomes. The human ability to manipulate fire led eventually to a substantially increased impact of human ignited fire on the environment after ~ 5000 years BP in the U.K. Other disturbances such as mining, deforestation and logging can also be detected in palaeoecological studies. The type of disturbances varies widely, and they impact on the vegetation dynamics in different ways; landscape fragmentation for agricultural purposes through biomass removal will usually reduce the frequency of fire events whereas removal of deciduous trees and the promotion of heather taxa such as *Calluna vulgaris* can increase fire frequency.

Figure 2-4 Under the yoke (burning the brushwood) painted by Eero Järnefelt, 1897 showing men and woman burn-beating in Lapinlaiti, Northern Savo, Finland.

As each activity impacts on the environment in different ways, interpretation of fire regimes needs to include decomposition of as many activities as possible using as many proxies as possible. However, it is difficult to distinguish natural climatically driven fire events such as ignition by lightning (Gromtsev, 2002) from ignition by human activity as the difference can be subtle. In the picture, ‘Under the yoke’ shown in figure 2-4, people are burning plant remains after crop harvesting at the end of the 19th Century. Charcoal is produced in this action similar to charcoal produced when vegetation ignites with a lightning strike. Differences do occur in the charcoal morphology depending on the temperature of the fire and the type of vegetation burnt and there are some empirical studies available looking at reflectance in charcoal fragments based on fire temperature and morphology of charcoal fragments (Enache & Cumming, 2006; Jensen, 2007).

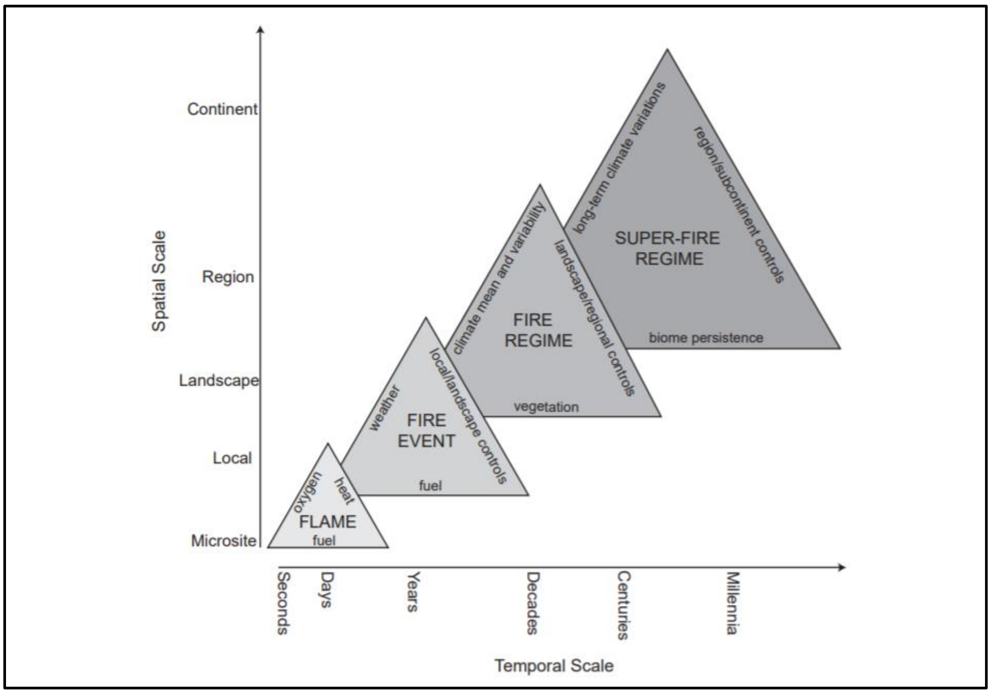


Figure 2-5 Controls of fire at multiple temporal and spatial scales conceptualised as fire triangles. From Whitlock *et al*, 2010. Spatial scale of parameters increases as the temporal scale increases.

The three parameters needed for fire to occur, oxygen, ignition and biomass, can be widened as in figure 2-5 above which denotes the increasing spatial-temporal scales (Taylor and Skinner, 1998; Whitlock, 2010). Climate becomes increasingly significant at the larger scales as does the extent of the area. Embedded within these conceptualisations is the impact of human activity. To develop an understanding of the complexities that human impact adds to fire-vegetation-climate relationships, analysis of long-term time series needs to be included in the interpretations of fire regimes (Whitlock, 2010). A fifth triangle, Scott *et al* (2018), depicts fire in deep time, with evolution of vegetation, climate change and atmospheric change as the three parameters of the fire triangle.

Fire events occurring over a time series is usually described as a fire regime. This is a key distinction as it is more likely that a charcoal fragment record will be described in terms of a fire regime rather than individual fire events. A fire regime can be defined as the full range of variability in fire activity within a given vegetation type, over the period of its existence (Whitlock *et al*, 2010). Holocene fire regimes are driven by top down mechanisms via the climate and bottom up mechanisms such as vegetation succession and human activity (Pyne, 1988; Whitlock *et al*, 2010; Clear *et al*, 2015; Carter *et al*, 2018). Both internal ecosystem pressures (e.g. succession) and external forcing factors (e.g. solar forcing) can alter a fire regime in any ecosystem. These pressures can impact positively or negatively on an ecosystem, be part of a natural ecosystem response, exert an additional level of impact under extreme conditions (e.g. storms) or they can be outside a normal ecosystem response under a human driver management system. In recent millennia, human driven management systems are more easily detected during and after periods of population expansion such as occurred during Bronze, Iron and Romano-British ages. Holocene fire regimes across Northern Britain have been shown in many studies such as Innes *et al*, (2010); Blackford & Innes, (2006); Tallis, (1983, 1990). Some of these can show disturbance events although it is not possible to identify which fire events are caused by people or are natural events. By analysing the parameters such as fire return interval and fire frequency with changes in pollen percentages or proportions, long term trends probably driven by climatic conditions and more intense, shorter trends or disturbance events can often be related to anthropogenic events (Clear *et al*, 2013).

Disturbance events during early Holocene millennia, where human activity often had a lighter impact on ecosystem dynamics, can be more difficult to detect and untangle, although some early human activity has had a profound effect on areas of the globe. For example, early human arriving in Australia ~40,00 years ago are thought to have used fire to control the vegetation and this is part of the reason for megafaunal extinction and the retraction of monsoon rains in the central areas of Australia (Roberts *et al*, 2001; Gillespie *et al*, 2006; Roberts, 2014). More recently, a relatively small number of people were instrumental in ecosystem shift around 700 years BP in New Zealand (McWethy *et al*, 2009; 2014). This implies that it is important to investigate the impact of early tribes on fire prone ecosystems such as upland U.K. moorlands to develop a full understanding of fire-vegetation-climatic relationships. However, the degree of impact of Mesolithic tribes on upland bogs in northern England in comparison to the impact of changes in climatic conditions is a debatable issue. Spikins (1999) suggested an estimate of 0.02 people per km^2 (compared to 427 per km^2 in England presently) for the early Mesolithic period. This was also suggested as an acceptable estimate by Preston (2012). Preston's research found that the Central Pennine regions was a highly used area by Mesolithic tribes and that their territories were larger than previously thought. Figure 2-6 shows that the majority of Mesolithic sites in the central Pennines were 450 – 499 m a.s.l.

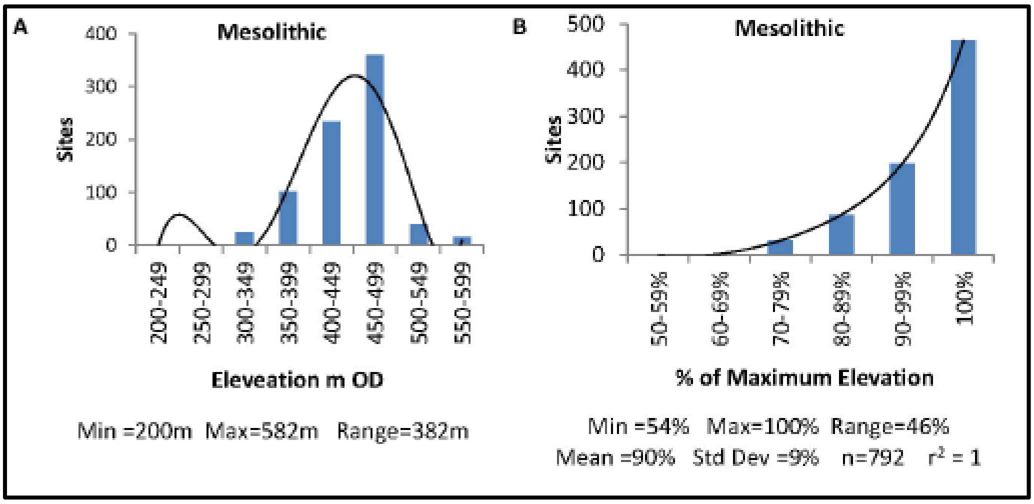


Figure 2-6 Number of Mesolithic sites at elevation from 200 to 599 m OD elevation in central Pennine Region (Preston, 2012). Permission granted by Paul Preston in 2018.

Such an intense use of the Pennine region by local tribes would imply that they could have a significant impact on the vegetation in this area. However, results for paleoecological studies for this period do not always provide clear interpretations as peat environments can have a complex history and drivers are difficult to untangle (Fyfe *et al*, 2018). Several studies that investigate human impact on U.K. Holocene woodlands in middle to late Holocene, for example (Stewart *et al*, 1956; Tallis *et al*, 1990; Innes & Simmons, 2000; Blackford *et al*, 2006, 2006a; Cayless & Tipping, 2002; Fyfe *et al*, 2012), have generally found that where humans and/or fire events are present, these drivers have a low level impact creating a diverse mosaic of vegetation assemblages. Mighall *et al* (2004) found evidence of Mesolithic clearing of forest taxa. Other research such as (Fyfe *et al*, 2018; Blackford *et al*, 2006; Tipping *et al*, 1995) have questioned the assumption that human activity was the main factor in creating open spaces within woodlands. Local geomorphological differences will create variety in how fire events and other disturbances impact on the local vegetation, but the influence of climatic conditions on upland areas should be seen in multicore studies. The impact of fire events during the Mesolithic/Neolithic transition in the U.K. has been investigated in several ombrotrophic bogs at varying resolution over different time periods. Studies such as those by Innes *et al* (2013) and Albert *et al* (2015) working in the North York Moors, Payton *et al* (2016) In N.E. England and Griffiths *et al* (2017) in Yorkshire and Humberside all found evidence of Mesolithic impact on the forest in a repeated pattern of disturbance and regeneration of woodland species where many samples include quantities of charcoal fragments. For the Peak District, several sites have been investigated for the effect of fire on soil properties such as Rosenburgh *et al*, (2013) who looked at post-fire chemical properties and Worrall *et al* (2013) which looks at carbon fluxes. Dartmoor, where peat development prior to 6000 years BP is similar to Robinsons Moss, is also a well studied area. Fyfe *et al* (2012) found local spatial differences in vegetation patterning.

For other upland regions such as the boreal forests across Northern Europe, the impact of early Mesolithic tribes also has relevance to fire-vegetation-climate relationships. These ecosystems are driven by a complex set of processes, and several local factors have an impact on long-term changes in forest composition (Kuosmanen *et al*, 2016). In northern Finland, Pitkanen (1999), found that regional warm and dry climatic condition probably drove an increase in fire frequency between 8000 and 4000 years BP, although local variations in a multiple core study by Mathijssen *et al* (2016) could be attributable to human ignited fires. Morris (2015) also found that climate was the main driver over the last 5000 years at three bogs in southern Finland with the additional possible impact of human populations. Kuosmanen *et al* (2016) in their study of unmanaged taiga forest in north western Russia found that during high intensity fire between 7500 and 7000 years BP, differences in vegetation composition were attributable to regional climatic differences. These studies show that climate was the main driver at these sites in Finland, but local conditions still have an impact on vegetation composition and succession.

2.4 Fire-vegetation models

A further approach in understanding fire-vegetation-climate relationships in relation to disturbance by human activity is the development of dynamic vegetation models. Including

fire ecology in these models is not without difficulties; however, this has progressed over recent years for example with the development of the LPJ- GUESS model. Fire can have either a natural or anthropogenic ignition however detecting the environmental conditions that support either of these ignition sources is not straight forward or easily achieved.
For the LPJ-GUESS model separating these ignitions sources is more difficult and less pertinent than being able to predict fire spread, so the latter is more developed for this model (Bradshaw & Sykes, 2014). One of the difficulties in determining human influence in the ignition of fires during the Holocene is that different drivers operate at a variety of spatial and temporal scales and it can be difficult to separate them in the proxy data. For example, fires usually occur during dry conditions, which can often be detected in the vegetation dynamics, however the fuel load i.e. amount of biomass needed for a fire to occur, can be the result of an increase in precipitation that occurred on a different temporal environmental cycle.
Natural processes constantly change landscapes. Differences in spatial vegetation dynamics due to other parameters such as altitude, topography, hydrology can also present difficulties for modelling fire-vegetation-climate relationships**.** Raw data can provide useful information to parametrise dynamic vegetation models. Spatial and temporal changes in regional vegetation assemblages can be identified through pollen grain and spore analysis (e.g. Tallis, 1991; Innes *et al*, 2010; Fyfe *et al*, 2018). Local vegetation dynamics can often be confirmed using macrofossil or fungal spore assemblages as they usually remain in the local area and are then incorporated into the paleo soil or peat although local vegetation dynamics are influenced by a complex set of factors and hence are too individual to be modelled by any currently available modelling approach (Kuosmanen *et al*, 2016).

Identifying the reasons for changes in vegetation requires the unravelling of complex natural processes that have direct influences and less direct influences through feedback mechanisms and long-term trends. Some recent papers such as Molinari *et al* (2013) used a modelling approach and found different dominant drivers during different periods across the Holocene for Europe. They concluded that climate and natural changes in vegetation were the dominant drivers during the early and middle Holocene whereas anthropomorphic activity was a significant driver during the late Holocene.

We now have many scientific techniques to aid the interpretation of human activity and the complex interactions between vegetation and climate such as the use of global climate models and dynamic vegetation models. We can parametrise these models by using palaeodata and as we continue to improve the models, we can, with increasing accuracy and detail, model past environments and forecast future scenarios for fire prone ecosystems. In one of their summaries in Chapter 5, Bradshaw and Sykes (2014), state that globally it is climate rather than humans that influence the extent of wildfires.

2.5 Climate

Climatic conditions are an integral ecosystem parameter and can be identified as a major driver for ecosystems across Earth. The transition from glacial to interglacial at the end of the Younger Dryas stadial heralded a sequence of changes in the terrestrial biosphere that although they varied across the continents did display general trends that can be detected. As this thesis is concerned with sites in northern Europe this section will focus on the climate in Europe. Between 13,000 to 12,800 years BP, during the late-glacial period, the climate was warm, with European temperatures reaching an average of 18 °C in the summer facilitating the growth of a *Pinus* – *Betula* woodland (Innes & Blackford, 2003). The transition from the glacial period, the Younger Dryas (which occurred between 12, 800 years BP until around 11,600 years BP) to the early Holocene, was generally rapid with abrupt increases in temperature seen in varved lake sediments (Martin-Puertas *et al*, 2017). During the early Holocene, changes in the sea surface temperatures in the North Atlantic were estimated to be up to 10 °C, around 4 - 5°C higher than present day along the flank of Norway and 2°C close to Greenland (Andersen *et al*, 2004). Pollen records from higher latitudes show that winter temperatures and summer temperatures during the early Holocene were warmer than present day (Prentice *et al*, 2000; Kaplan *et al*, 2003). A dip in temperature around 8.2 k years BP, that can be seen in the modelled Holocene temperature curve (figure 2.9), is recorded in many areas in North America and Northern Europe. For example, in a recent paper by Carter *et al* (2018). However this temperature downturn is more elusive in records for the British Isles. The orbital forcing that led to the general temperature amelioration in the northern hemisphere during the early Holocene was strongly influenced by the release of warmer water from the Laurentide ice sheet and the ensuing effects this caused on ocean circulation and its feedback mechanisms and the developing forests that subsequently replaced the ice (Oldfield, 2005).

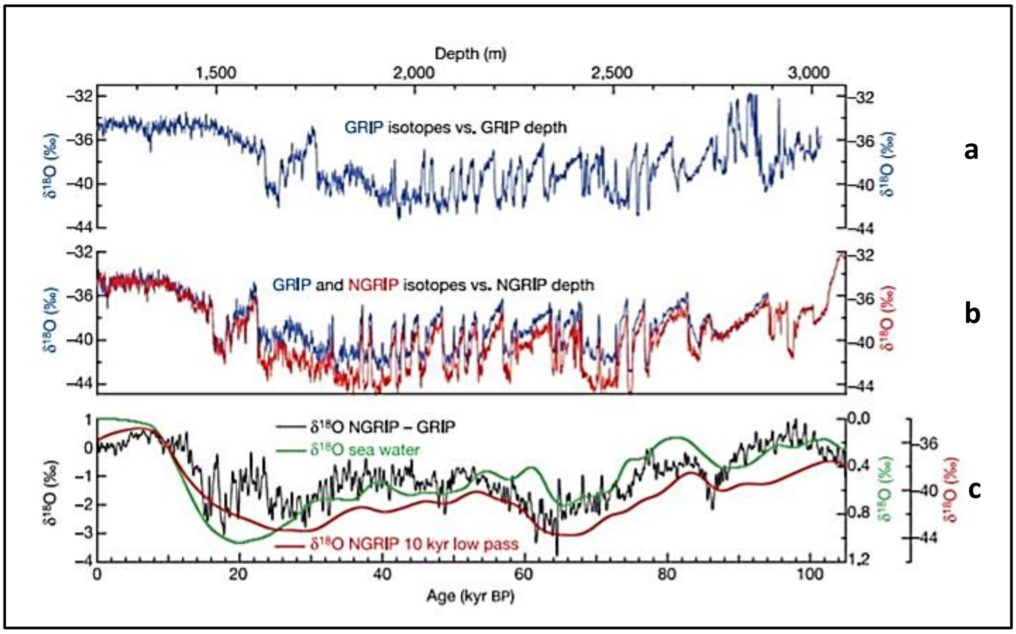


Figure 2-7: NGRIP oxygen isotope record compared with the GRIP oxygen isotope records for Greenland. GRIP oxygen isotopic profile (blue), a; The NGRIP oxygen isotopic profile (red) b, (a and b plotted against depth at NGRIP); The difference between the NGRIP and GRIP oxygen isotopic profiles plotted above on the GRIP2001/ss09sea timescale15 in 50 yr resolution (black) with sea level change record (green) and a 10-kyr smoothed oxygen isotope profile from NGRIP (red), c. Taken from Anderson (2004). Permission granted for individual use.

Difficulties in modelling climate data arise for the last 3000 years and are due to variability within the system. For example, variability differed in the northern and southern hemispheres, driven in part by the El Niño oscillation in the southern hemisphere (Moy *et al*, 2002; Woodroffe *et al*, 2003; Gagan *et al*, 2004) and the North Atlantic Oscillation in the Northern hemisphere (Hurrell *et al*, 2003). These oscillations and other changes in extreme weather conditions do not form patterns that can be modelled accurately yet (Oldfield, 2005).

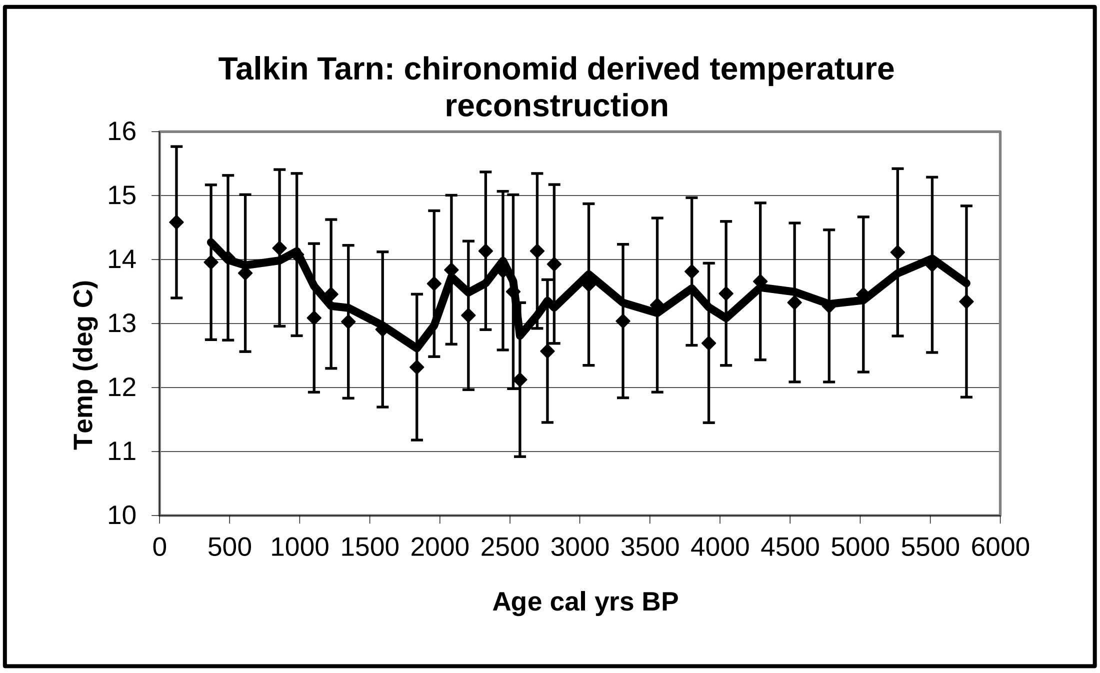


Figure 2-8: Chironomid derived temperature reconstruction for Talkin Tarn for last 6000 yrs. (Langdon, 2004) with permission by Peter Langdon.

1.4 wet (Hughes, 2000) 1.6 wet (Charman, 2006) 1.7 wet (Hughes, 2000)
2.32 – 2.04 wet (Hughes, 2000)
2.65 cool (Brooks, 2016)
2.4 warm (Hughes, 2000)
2.75 wet (Langdon, 2004) 2.75 wet (Van Geel, 1990) 2.76 wet (Charman, 2006)
3.17 – 2.86 wet (Hughes, 2000) 3.17 wet (Charman, 2006) 3.3 wet (Langdon, 2004) 3.5 wet (Charman, 2006) 3.9 wet (Langdon, 2003)
4.41 – 3.99 wet (Hughes, 2000)
5.3 – 4.0 cold (Tallis, 1990)
5.3 wet (Hughes, 2000)
5.6 cold (Langdon, 2004)
5.7 wet (Barber, 1981) 5.8 – 5.6 wet (Cayless, 2002)
5.8 dry (Tipping, 2000) 5.9 dry (Barber, 1981) 5.9 dry (Hughes, 2000)
6.4 dry (Barber, 1981) 6.6 dry (Tipping, 2000)
7.83 -7.32 wet (Anderson,1998) 7.8 wet (Hughes, 2000
8.2 cold (Brookes, 2003)
8.2 arid (Tipping, 2000)

Table 2-2: Various Holocene Climate shifts across Great Britain as identified in stated literature.

Several climatic trends based on palaeoecological records have been constructed for the British Isles, however due to climatic variability described above and vegetation lag effects, it is difficult to correlate these records (Schulting *et al*, 2010), although some wet/dry shifts have some agreement. One of the more accurate types of record use fossil chironomid remains found in lacustrine sediments and transfer functions to describe temperature changes, (Langdon *et al*, 2004) see figure 2-8. Others use testate amoebae remains and a transfer function (Woodland, 1998; Charman *et al*, 2006), for bog surface wetness (Hughes, 2000; Charman, 2010; Anderson *et al*, 1998; Hughes, 2004). Some evidence for cross-validation has been shown in papers such as Charman *et al*, 1999; Chiverrell, 2001; Langdon, 2004; Blundell & Barber, 2005). Ombrotrophic peat bogs, a key sediment type for this project, are sensitive to hydrological changes that are linked to changes in precipitation. These ecosystems are also linked to vegetation response to changes in climatic conditions. It is difficult to separate these two signals (Bradshaw & Sykes, 2014) but finding an independent climate signal to interpret fire – vegetation relationships is important to remove circularity in any interpretation.

Modelled data of Holocene temperature trends for multiple simulations from 11000 years BP (Zhang *et al*, 2018) is shown in figure 2-9. This graph shows an agreement between the simulations for a temperature rise from 7800 – 5800 years BP and a general decreasing temperature trend up to present day. These trends however would not be seen when viewed on a scale reaching back to 400,000 years where the longer Quaternary fluctuations can be observed as in datasets derived from ice cores such as the GRIP and NGRIP ice cores seen in figure 2-7 (Anderson *et al*, 2004).

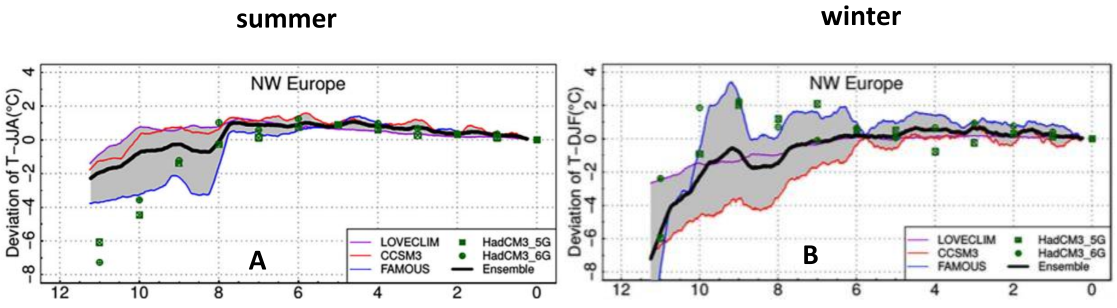


Figure 2-9: Modelled Holocene summer temperature trends (shown as deviations from the average temperatures for summer (A) and winter, (B) in ˚C) for NW Europe where multiple simulations have good agreement and corresponding multi-model ensemble mean (based on three transient simulations). The grey shading indicates the ensemble range. Early Holocene summer cooling of 2-3 ˚C and winter cooling of 8 ˚C. From Zhang *et al* (2018). Licence no. 4590240883950.

The time period covered in this study i.e. mid to late Holocene is likely to be representative of the variability that will interact with anthropogenic forcing over the next few centuries and is the 'background noise' against which any signal of anthropogenic forcing will have to be detected (Oldfield, 2005)

2.6 Peat: A sedimentary archive of palaeoecological information

Definition

There are two main types of mire systems; firstly, those that receive atmospheric water and ground water from outside of the mire system are generally referred to as fen systems and secondly those that only receive water directly from the atmosphere with the centre of the mire elevated above the influence of runoff from the surrounding slopes (Berglund, 1986); these second types are generally described as ombrotrophic bogs.

Peat sedimentary deposits are important archives of environmental information. Peat is laid down linearly and hence can be utilised in paleoenvironmental reconstructions (Marrs *et al*, 2018; Charman *et al*, 2013; Barber *et al*, 2003). The unique properties of peat deposits mean that they are highly sensitive to hydrological change (this is particularly relevant for ombrotrophic mire systems) which means that they can provide information on changes in the water level and hence on paleoclimates (Berglund, 2003). Peat deposits usually contain a range of well preserved botanical remains that can be analysed to reconstruct various environmental conditions during the Holocene. Dating peat sediments is not without difficulties, radiocarbon dates often reveal younger dates due to contamination through root penetration and contamination by mobile humic acids (Gale *et al*, 2009; Gallego-Sala *et al*, 2016).

Mire initiation can often be detected by analysing pollen datasets in combination with geochemical analysis which can be an interesting way to investigate the influence of natural successional development of a mire system particularly for early Holocene initiation where the impact of human activity can be minimal. This is discussed with regard to Robinsons Moss, Peak District, an upland ombrotrophic bog in chapter five. Here charcoal fragments, pollen and fungal spores are analysed in combination with geochemical data derived from X-ray Fluorescence (XRF) and Near Infra Red Spectroscopy (NIRS) analyses for the lower section of the core. Timing of mire development in U.K. mire systems is also an interesting concept. There is evidence for early development of bogs driven by climatic conditions around 9000 – 8000 years BP and later shifts to bog conditions around 6000 -5000 years BP. These later initiations and expansion of peat systems are thought to have been greatly influenced by an expansion of human populations although other research also implies that these initiations were also climate driven (Bradshaw & Sykes, 2014). This is also discussed in chapter five. Upland sites in particular are sensitive to changes in environmental conditions. Changes in forest/scrub altitude, climatic shifts and disturbances can all be detected at sites such as Robinsons Moss 500 m a.s.l.

Peat initiation

Across the U.K. many forested areas succeeded through several stages and sub stages into open moorlands. Some moorlands, such as those in the Faroe Islands, developed naturally in relationship with the climate and other environmental conditions (Lawson *et al*, 2008), whilst others were subject to the major influence of the action of people (deforestation, agriculture) and fire which can be driven by natural or anthropogenic causes. These open moorlands, however, they were formed, continue to be subject to the vagaries of natural processes and human activity. People have continued to interact with moorland landscapes through use of environmental services, recreation and conservation ever since the arrival of early people across Northern Europe, who have lived, worked and changed these landscapes in different ways throughout the millennia. As we increased in number and developed technology, we have changed the ways in which we view natural resources and the natural world. Our interaction has also been influenced by contemporary climatic conditions; deterioration and amelioration in climatic conditions has influenced how we have made use of upland habitats.

Moorlands are variously described and defined depending upon the organisation, country and field of research. They are described in the IUCN UK 1-10 Peatland Briefings (5th November 2014) and summarised here; A bog is a wetland which is waterlogged only by direct rainfall whereas a fen is waterlogged by groundwater enriched by the chemistry of mineral soils. The waterlogging prevents the complete decomposition of dead material which accumulates as a thickness of peat. Peat is a relatively amorphous organic deposit which consists of semi-decomposed plant material mixed with varying amounts of mineral or inorganic matter. For U.K. peat bogs, the content of mineral matter may be as low as 2% by weight. The international term for a peat forming system is a mire (IUCN UK 1-10 Peatland Briefings, 2014). Studying the successional changes in moorland habitats can reveal the temporal and spatial environmental conditions that drove these landscapes throughout the Holocene. This research shows transitions from woodland to open moorland in sites across northern Europe and explores the impact of climatic changes such as the Holocene thermal optimum and subsequent climatic deteriorations and ameliorations. Molinari *et al* (2013) showed that fire was a main driver during early Holocene and that climate and climate combined with changes in vegetation drove landscapes across Northern Europe during the middle and late Holocene. Peatland habitats and the plants that populate them are vulnerable to changes in climate. As globally significant carbon stores their future condition is of global significance (Allen *et al,*, 2013; Marrs *et al,* 2018).

Once a peat moorland has established, many of them have been managed so that they remain as moorlands. There are many moors in Great Britain that are either privately owned and managed or owned by organisations such as United Utilities and managed by National Environmental Organisations such as Natural England. Many are subject to National and International Conservation designations. In the recent past, economic activities such as peat extraction and grazing by sheep has damaged or even destroyed many peat habitats (McCarroll *et al*, 2016). Three quarters of the world's remaining moorlands are in the UK and moorland covers about 25% of UK uplands (Moors for the Future, 2007; Allen *et al*, 2015). Blanket peatland covers 1.5 million hectares in the UK of which approximately 14% is in England (McCarroll *et al*, 2016; Jackson and McLeod, 2000). The distinction between upland and lowland peat systems can be viewed from various environmental and sociological aspects. Current treeless upland areas deemed to be 'cultural landscapes' that are maintained by current management practice. However, the distinction between upland and lowland is a relatively recent way to describe peat habitats and is based more on cultural definitions than environmental (Davies *et al*, 2016). There are differences in altitude, geomorphology and environmental conditions that define floral assemblages and successional pathways that are used by environmental and conservation bodies such as those used by the Biodiversity Action Plan; Priority Habitat Descriptions that help to define their status in terms of biological diversity and socioeconomic value. However, these definitions are less appropriate as we travel further back in time prior to recent population expansions and under different climatic conditions such as during the early Holocene. For this study, the term upland is used in reference to altitudinal sensitivity to changes in climatic and other environmental conditions which define vegetation assemblages (Tallis, 1991).

The formation of blanket bog is restricted to special climatic conditions. Their location is restricted to temperate hyperoceanic areas of the world (except for the Ruwenzori Mountains in Uganda). As the climatic conditions that maintain their status change, it should be possible to detect these changes by reconstructing Holocene environmental conditions.

As with other sedimentary deposits, there are advantages and disadvantages of using mire systems in palaeoecological reconstructions. Due to topographical differences, a bog surface usually has a variable pattern of wetter and drier areas. This should be taken into consideration in any hydrological analysis. Hydrological changes are not one of the focussed areas of investigation for this study as this would require a transect of cores across a bog system to be analysed.

2.7 Vegetation – fire dynamics

The length of the growing season determines the amount of biomass available for burning. The growing season at 500 m a.s.l. is 65 days shorter than at sea-level at same latitude

(Innes, 2003). Altitude and rainfall are key variables in determining the length of the growing season. Much of the rainfall in the U.K comes from westerlies. The amount of rainfall varies on an east-west gradient, with more rainfall in the west than the east. Topography and biogeographical trends determine the drainage and the dominant taxa in the vegetation community of an upland area, so these vary across the U.K. For example, recent data suggest that in the Peak District, 32% of the moorland vegetation is dominated by *Calluna* and 25 % dominated by species of *Vaccinium* (Innes & Blackford, 2003).

The areas of England above 200 m a.s.l. are shown in figure 2-10 and include the upland areas of North York Moors, Peak District, Dartmoor and Exmoor. Heather taxa such as *Calluna vulgaris* are major species found in the U.K. sites used in this study. *Calluna vulgaris* and other heather taxa will grow at a wide range of altitude as shown in the heather coverage map (figure 2-11).

The fire history of upland differs from the fire history of lowland within the British Isles (Jones unpublished), 'Holocene stand-scale forest dynamics of the British Isles'. Figure 2-12 shows this difference. The uplands, here defined as being above 200 m a.s.l. showed differences in charcoal values for most of the 500 year bins from 11,500 – present day although some general trends can be seen in both upland and lowland areas. Lower charcoal values from 7000 – 4000 years BP are also seen in figures 2.13 showing macrocharcoal values for sites used in this thesis. Both graphs also show an increase in fire events from 5500 to 5000 and from 45000 – 4000 years BP. The burning of heather taxa is important in fire- vegetation relationships for modern ecology, however there are ecological and geographical differences that can impact on fire – *Calluna* relationships. This again shows the importance of local high resolution studies for research involving Holocene fire – vegetation climate dynamics.

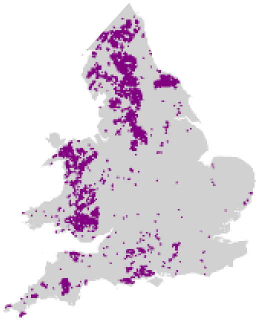


Figure 2-10: Heather coverage in England and Wales (www.Moorlandassociation.org)

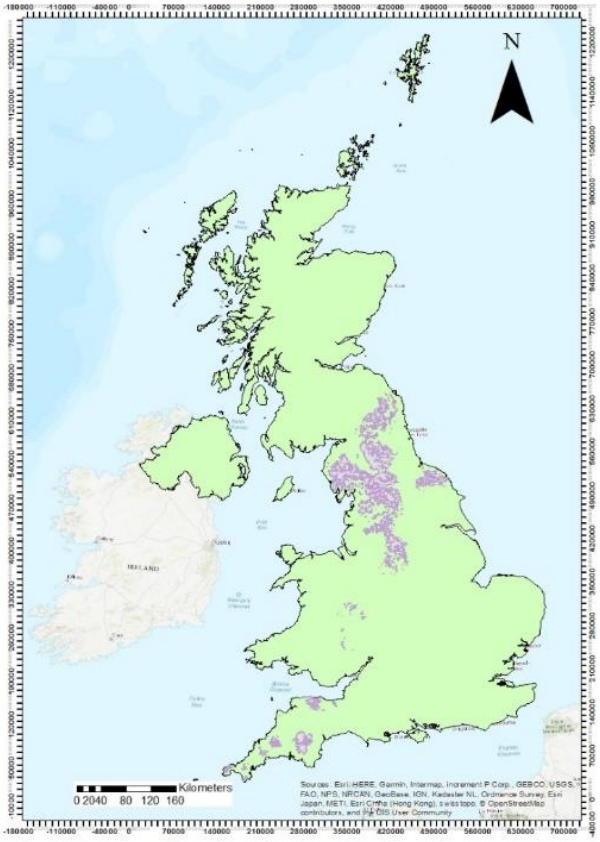


Figure 2-11: Land in England and Wales above 200 m a.s.l. (purple).

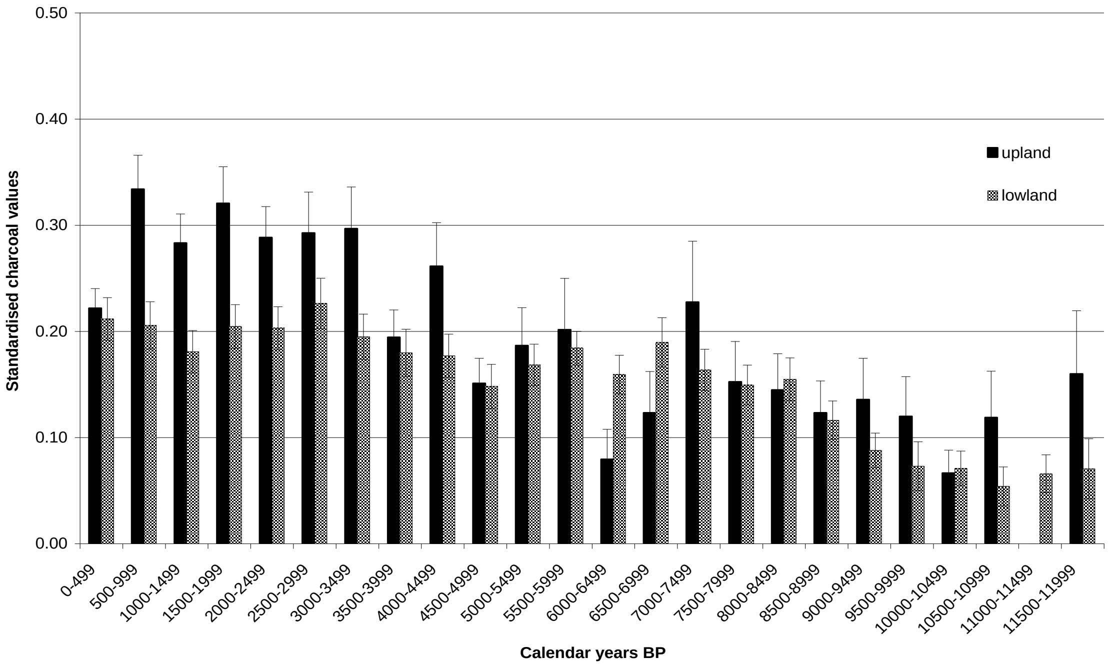


Figure 2-12: From Jones (unpublished). Upland (> 200 m a.s.l.) and lowland (< 200 m a.s.l.) mean standardised charcoal values in 500 years bins for the British Isles.

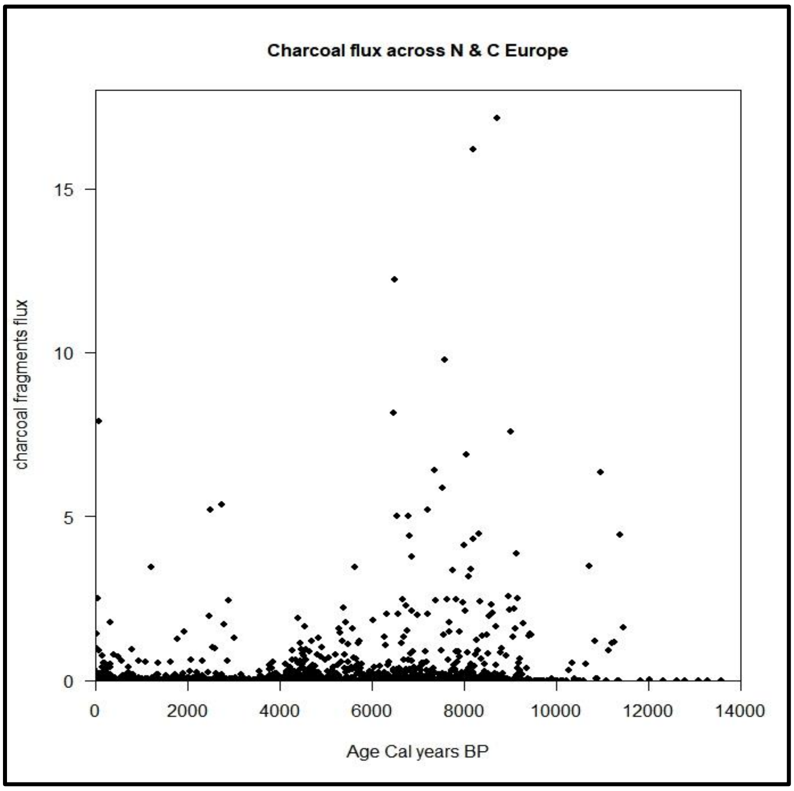


Figure 2-13: Charcoal fragment flux values (mm²cm² year) for nine sites across Europe (includes sites not used in the RDA calculations). Data derives from various projects undertaken by the author to show results from a wide range of sites.

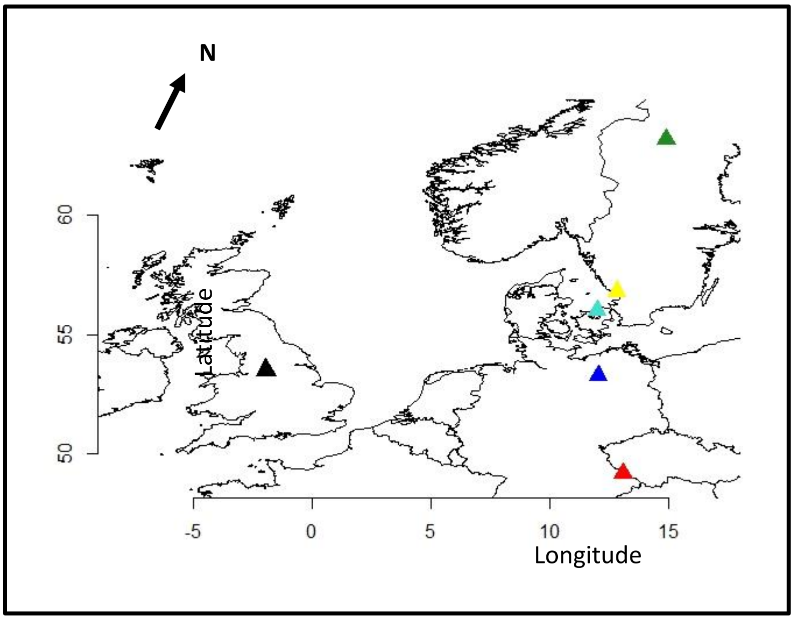


Figure 2-14: A map showing the location of eight cores (macrocharcoal fragments processed using the image analysis method described in chapter three). This map shows the sites but the analysis did not include the same cores as in figure 2-13. U.K. one core (black triangle), Denmark one core (turquoise triangle), Germany one score (blue triangle), Sweden one core (yellow triangle), Norway, three cores (green triangle), Czech Republic, one core (red). These were all processed using the image analysis method described in Chapter three. All data compiled by Karen Halsall as part of this thesis.

Despite the limited number of sites (figure 2-14) compared to the geographical area, it is interesting to see temporal trends in the charcoal fragment data across northern and central Europe which suggest links between the climatic conditions and fire events (Simmons, 2003) . A greater range of charcoal fragment flux values occur between 9000 – 5000 years BP than at other times. There is also a peak in fire intensity ~ 2500 years BP and during the last few hundred years. There is a reduction in values between 3500 – 2500 years BP. These trends will be discussed later in this thesis.

Chapter 3 Towards a standardised method for macroscopic charcoal fragment quantification using image analysis

3.1 Abstract

Charcoal fragments that accumulate in sedimentary deposits can be used as a proxy for fire events and in the reconstruction of Holocene environmental histories. Image analysis is one of several methods that can be used to process and quantify macroscopic charcoal fragments found in sedimentary deposits such as lacustrine, peat or forest hollow. The size of charcoal fragments usually studied in Holocene reconstructions ranges from black carbon particles to fragments > 2mm in length. Microcharcoal is usually defined as being > 100 µm. There are currently many different preparation and quantification methods for macrocharcoal charcoal fragments and there is not a standard method, although there are similarities between types of procedures. The global charcoal database lists over 120 different combinations of isolation process and quantification units (https://www.paleofire.org).

Acquiring detailed information concerning environmental changes tends to increase with higher resolution studies, but the disadvantage is the increase in time needed to process sediment samples at high resolution. Many fire histories are of poor resolution and comparison of records employing different methods means the data need to be statistically transformed, for example, the method described by Power *et al* (2010) which converts quantities using z scores in a triple transformation process. Data transformation can lead to a reduction in the sensitivity in the data.

This chapter presents a relatively quick method of digital image analysis of macrocharcoal fragments using simple equipment and free software that can be used for any type of sediment, at any resolution. Techniques for removing non charcoal organic material, large mineral matter and “clouds” of *Sphagnum* plant parts are included.

3.2 Introduction

3.2.1 *Fire regimes*

Fire events occurring over a time series are usually described as a fire regime. A fire regime can be defined as the full range of variability in fire activity within a given vegetation type, over the period of its existence (Whitlock, 2010). Holocene fire regimes are driven by top down mechanisms through climate and bottom up mechanisms such as vegetation succession and human activity (Pyne, 1997; Whitlock *et al*, 2010; Clear *et al*, 2013; Carter *et al*, 2018). Studies of fire regimes can either focus on a single site or alternatively a composite of several sites can be analysed. The choice of method depends on the scale of the research questions within the study. For regional, country or continental studies, a composite analysis of several sites is appropriate. Molinari *et al* (2018) investigated the influence of different drivers on changes in North American and European boreal forests biomass burning during the Holocene and found that climate and then fuel composition were the dominant drivers with land use change being of only marginal significance. Although the study by Molinari *et al* (2018) does not include the U.K. and concentrates on boreal landscapes, it does show that climate has a greater influence on biomass burning as opposed to human activity when we extend the time scale back thousands of years instead of merely hundreds. It also shows that it is important, where possible, to include the impact of human influence on ecosystems as they can have a significant effect on the climatic biofeedback mechanisms operating at a larger scale than other drivers (Whitlock *et al*, 2010).

The identification and interpretation of fire regimes within dynamic ecosystems is a complex and poorly understood major Earth system process (Bowman *et al*, 2009). Fire continues to be a major disturbance agent in most ecosystems (Whitlock *et al*, 2010) and could increase in severity if changes in climatic conditions reported in the latest IPPC report (2018: https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pd) in combination with human management of fire prone ecosystems, leads to an increase in the biofuel load during higher summer temperatures (Leys *et al*, 2013). Wildfires produce and distribute pyrogenic organic matter, of which charcoal is a main component particularly when forests burn. As charcoal remains in soils and sediments for millennia (Scott*,* 2010; Santin *et al*, 2016), paleoenvironmental records are therefore a legacy of spatial and temporal patterns in fire events (Pyne, 1997; Bond *et al*, 2005; Whitlock &

Larson, 2001). The main tool in the identification of fire regimes is the isolation, quantification and statistical analysis of charcoal fragments. However, reconstructing fire history depends upon the understanding of the processes controlling wildfire, their ignition, spread and subsequent charcoal accumulation (Hawthorne, 2016, 2018). A schematic for charcoal taphonomy is shown in figure 3-1.

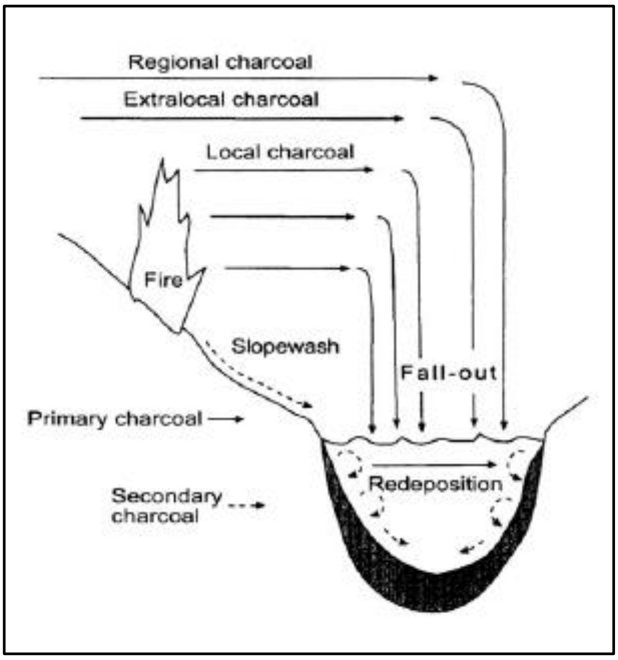


Figure 3-1: Schematic diagram illustrating the sources of primary and secondary charcoal in a watershed. From Whitlock & Larson (2001).

Fire events and hence fire regimes, represented by peaks in macroscopic charcoal fragments found in lake, bog and forest hollows (Tolonen, 1986) can be analysed using statistical programmes such as CharAnalysis (Sugita, 2007a, 2007b) and ARCO (Finsinger *et al*, 2014). High resolution datasets have been used to reconstruct global, continental, regional and local fire regimes in a wide range of ecosystems. Ecosystem drivers can be determined at a variety of scales depending on the resolution of the studies and the range of proxies used for paleo-environmental conditions. Further information about the interaction between these drivers is still needed to gain a full understanding of the role of fire in dynamic ecosystems during the Holocene (Adolf *et al*, 2017 Gallego-Sala *et al*, 2016). It is vital that data sets can be correlated significantly between sites and regions by minimising the effects of within and between core variability (Halsall *et al*, 2018). Due to the variable nature of fires, and the fact that all fires are unique, this is a particular issue for analysing charcoal fragments. This can be improved by the development of careful standardised methodology for the isolation and quantification of charcoal fragments, a mechanism that has not yet been achieved (Whitlock *et al*, 2010; Conedera *et al*, 2009).

3.2.2 *Fossil Charcoal*

Fossil charcoal, derived from organic material, can be found in sedimentary deposits across the globe. The earliest evidence for charred plant fragments occurs during Late Silurian, when oxygen levels were above the present atmospheric level of 21%. Since then, fire has been integral in the formation of most ecosystems (Bond *et al*, 2005; Colombaroli *et al*, 2010). Charcoal is a relatively inert substance which allows for many different methods for isolation and subsequent quantification; the choice of method used in a study will depend upon the research questions and the temporal scale under investigation. See table 3.1 for a list of common charcoal methods.

Fossil charcoal can be described as opaque, angular and usually planar (Smol & Last (Eds)., 2001: Whitlock & Larson, 2001) but also by its lustre and the presence of anatomical features of the original plant. It is formed from incomplete combustion of organic material in the temperature range 200 - 600 °C (Conedera *et al*, 2009).

For paleo reconstructions, historically, charcoal fragments have been identified at different scales; from dark bands in cores, to microcharcoal particles on pollen slides and as fragments visible to the naked eye in macrofossil studies. Several different methods for isolating and quantifying charcoal fragments are available such as chemical isolation from sedimentary rocks, as bio layers using resin, in thin section preparation and recent methods with macrocharcoal using various bleaching techniques.

Although charcoal fragments can be isolated from sediments using a variety of methods, ideally, every precaution should be taken to preserve the form of the original fossil charcoal population, minimise particle fragmentation and loss and thus ensure that the charcoal index reconstructed provides a true representation of the deposited and sampled charcoal (Rhodes *et al*, 1998). Calibration studies that determine modern charcoal source areas are few and far between, so the usual goal of quantification is to recreate trends in local fire history and the mean fire return interval (Conedera *et al*, 2009).

3.2.3 *Examples of methods*

The majority of fossil microscopic charcoal analysis published over the last six decades quantified charcoal on pollen slides however there are other methods that have been used. Different methods have different biases in the size of particles that they are quantifying. Innes *et al* (2000) followed the method described by Robinson *et al* (1984) using four size classes for fragments retained on a 180 µm sieve used as part of the pollen grain preparation. Froyd (2006) counted microscopic charcoal particles on pollen slides using the point count estimation method of Clark (1982) and also used macroscopic charcoal analysis following the methodology of Millspaugh and Whitlock (1995) which uses 5cm^3 sediment sieved through nested sieves (125 and 250 µm). The particles were then counted using a stereomicroscope at x40 magnification using reflectivity and ability to be crushed as indicators of charcoal recognition indicators. These were then tallied in three size classes. In Robin *et al* (2012) macrocharcoal fragments were sieved at 200 µm and then hand sorted prior to image analysis. Bradley *et al* (2013) analysed images of charcoal fragments sieved at 300 µm. Carcaillet *et al* (2010) identified that minimum mesh size (for local fires) and sediment volume (for replicable data) are critical aspects of charcoal fragment analysis.

The correlation of data between methods was investigated by Ali *et al* (2009) and this study is supported by Tinner & Hu (2003) and Carcaillet *et al* (2007) in reporting strong correlations between the number and area of charcoal and that differences between comparable sites is probably due to taphonomic differences. Ali *et al* (2009), concluded that count, area and volume provide comparable fire history interpretations if the analytical techniques are insensitive to variability between the mean and variability both within and between time series, however this research used only lake sediments statistically treated with the CharAnalysis programme. This is a large scale study so this might not necessarily be the case for other studies comparing untreated empirical data using Kendall rank correlation coefficient (for non-parametric data). Variability between cores can be desensitised using large volumes (~ 10 - 12cm^3) as suggested by Adolf *et al* (2017). Whitlock and Larson (2001) encourage the use of more rigorous methodological approaches and being more explicit in assumptions to produce more easily compared and interpreted results. Tinner & Hu (2003) showed that area concentration (area / mm^2/ cm^3) and number concentration (number of charcoal particles / cm^3) of charcoal particles on pollen slides are strongly correlated and as long as the same pollen preparation technique is used, the regression equation for predicting area concentration from one site can be used to predict area concentration from other sites as long as small particles (< ~10µm) and large particles are eliminated (Finsinger and Tinner 2005). Finsinger *et al* (2008) suggest that microscopic charcoal analysis is not a suitable technique for quantitative estimates of total charcoal content but is suitable for reconstruction of regional fire history.

3.2.4 *Global Charcoal Database (GCD)*

The Global Charcoal Database (GCD) is a public-access database created by the Global Paleo Working Group (GPWG), supported and funded by the Past Global Changes International project, PAGES. The two main methods used in data accepted in the Global Charcoal Database (GCD) are pollen slides and sieving which are used at 50 % and 37 % of the sites respectively. The composite diagram below (figure 3-3) shows sites above 300 m a.s.l. extracted from the GCD (figure 3-2).

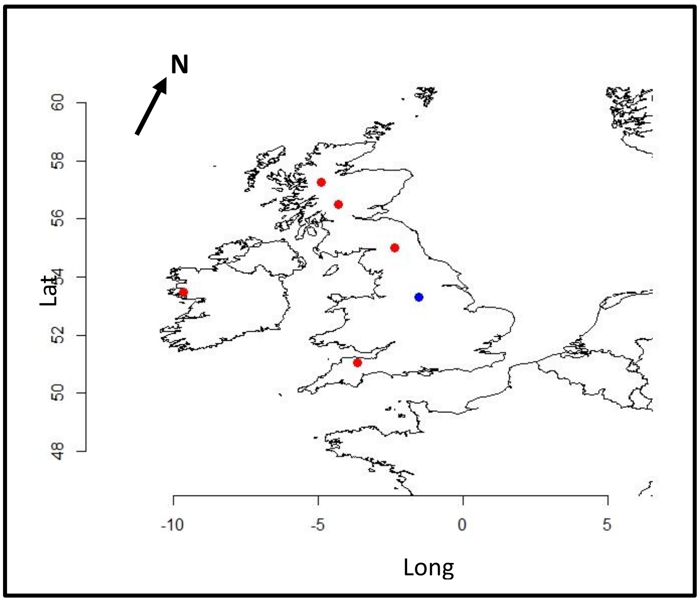


Figure 3-2: Site locations within the British Isles extracted from the Global Charcoal Database used in the composite graph figure 3-3 (red points) and Robinsons Moss (blue point) to show geographical location.

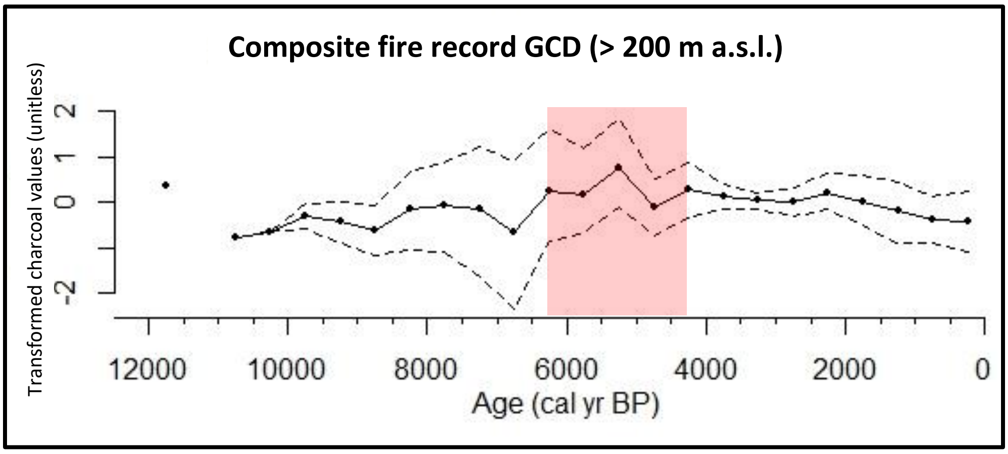


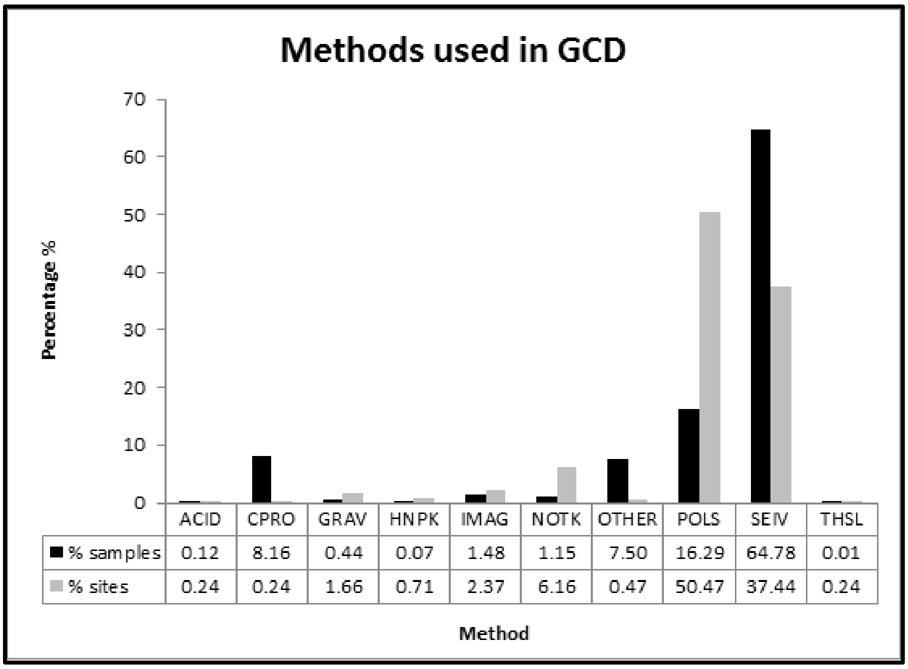
Figure 3-3: Composite graph of 5 sites over 200 m a.s.l. within British Isles extracted from the GCD (Power et al, 2008) with 500 year bin widths plotted with 0.5th and 95th percentile confidence intervals (top and bottom broken lines respectively). Red bar indicates a temporal peak in charcoal values. Y axis shows transformed charcoal data (Power, 2010).

This composite diagram shows that for these sites, fire increases post 6800 and remains relatively high through the Mesolithic / Neolithic boundary to around 4200 years BP and then fire events generally reduce until the present day.

There are currently 405 sites registered on the Global Charcoal Database and 45 on the British Isles Charcoal Database (five sites are on both) The aspects of methodology that vary on the GCD are units of measurement, method and sample volume.

Method	Description	Number of different units	Number of sites
ACID	Acidification of sample using gas chromatography to measure elemental carbon (Verardo et al, 1990)	1	1
CPRO	Cumulative probability (95% confidence interval) alluvial soil charcoal	2	7
GRAV	GRAVIMETRIC chemical assay (Winkler method)	1	3
HNPK	Hand-picked charcoal from soil samples	4	10
OMAG	Charcoal particles identified by imaging software	122	26
NOTK	Not Known	1	2
OTHER	Other	67	213
POLS	Pollen slide	30	158
SEIV	Sieved samples	30	158
THSL	Charcoal identified in thin slices (soil micromorphology)	0	1

Table 3-1: Different methods used in the Global Charcoal Database (2017).



	ACID	CPRO	GRAV	HNPK	IMAG	NOTK	OTHER	POLS	SEIV	THSL
■ % samples	0.12	8.16	0.44	0.07	1.48	1.15	7.50	16.29	64.78	0.01
▨ % sites	0.24	0.24	1.66	0.71	2.37	6.16	0.47	50.47	37.44	0.24

Figure 3-4: Percentage of sites in the Global Charcoal using each method described in table 3-1.

There are eight different known methods recorded on the Global Charcoal Database (see figure 3-4 and table 3-1) and for each of these methods there are different units used. For example, for samples that quantify charcoal fragments on pollen slides, there are 67 different units recorded over 213 sites and for sieved samples, 30 different units are recorded for 158 sites. 107 different units are recorded where the method is known and 19 different recorded units where the method is unknown. There are 26 different known different sample sizes.

3.2.5 *Compiling datasets that have used different methods*

To compare records, Power *et al* (2010) suggests a standardisation method by (1) rescaling the values using a minimax transformation, (2) transforming and homogenising the variance using the Box–Cox transformation, and then (3) rescaling values once more to Z. Whilst standardisation allow datasets to be compiled, there is a subsequent loss of sensitivity in the data which is relatively irrelevant for global studies but becomes more significant at smaller scales.

3.2.6 *Digital Image Analysis of macrocharcoal fragments*

Data for this study are derived from isolating and quantifying macrocharcoal fragments found in peat bogs, lakes and forest hollow sediments as a proxy for fire events. The method described below is adapted from Mooney and Radford (2001) and Mooney and Black (2003) using a sieving preparation method and digital image analysis. Digital image analysis can be used quickly and cheaply to create datasets for area, volume and shape indicators for large sub samples of charcoal fragments. The area of each fragment can be identified more accurately if the fragments can be isolated from all other organic or mineral matter. Charcoal fragments are identified by setting the threshold value (unitless) so that particles with a higher value only are included in the analysis. In the presence of other particles, this threshold often has to be lowered to isolate charcoal fragments from other dark particles (Whitlock *et al*, 2010). This study describes methods for improving the accuracy of measuring area of charcoal fragments by removing the non-charcoal organic matter from the analysis and so allowing for a higher threshold value and increasing the charcoal area that is recorded. To obtain a threshold that will suit most if not all of the samples, the following technique was used. A charcoal particle would be visually enlarged until individual pixels were visible. The threshold was set at a value where no change was

seen in the pixels over at least 2 threshold values. This was repeated for several charcoal particles from different samples so that a mean value could be determined.
Image analysis has been used successfully in studies such as (Carter *et al*, 2018; Robin *et al*, 2012; Mooney *et al*, 2003). Higher resolution images using more sophisticated cameras, video grabbers and image display software can improve the method. However, these can increase costs. This study tests the use of the free software ImageJ and a budget priced digital camera (Canon Ixus 265 HS with 12x optical zoom, 16.0 megapixel CMOS).

Examples of potential limitations for using image analysis in combination with a bleaching processing include:

1 The use of bleach is thought to have a negative impact on the amount of charcoal that is analysed post bleaching i.e. the bleach (or sodium hypochlorite) reduces the area of each charcoal fragment.
2 Very dark organic or mineral particles could erroneously be included in the total area value for each sample. Ideally, only charcoal fragments remain in the petri dish or they can be easily isolated.
3 The choice of the greyscale threshold value is subjective and will impact on the resultant area values.
4 There needs to be a compromise taken between how 'clean' the images are, and the time taken to achieve this. Charcoal fragment identification becomes more time consuming to resolve when other organic or mineral matter is present in the image.

3.3 Method for macrocharcoal fragments

3.3.1 Sample Preparation

Volumetric measurement

479 subsamples between 2 – 3 cm^3 were measured by volume displacement for every 1 cm of the core taken from Robinsons Moss. For some of the samples the amount of charcoal in this volume of sediment was onerous to process for area estimation, however for other samples that contained only a few charcoal fragments, would a smaller sample size have given a less significant reflection of the charcoal concentration for that time period? A compromise has to be reached in these circumstances. Carcaillet *et al* (2001) found that 1 cm^3 appears to be the minimal volume to obtain accurate results. Although Schlachter and Horn (2010) found that 1 cm^3 may not yield robust inferences of fire history. 1cm^3 sub

samples may be sufficient, although 1cm³ sub-samples are not as representative of the charcoal fraction as 2 or 3 cm³ especially when only a low number of fragments are likely to be found, so between 1 – 2 cm³ is recommended however, 2 – 3cm³ samples may be necessary (Mooney & Tinner, 2011). If there are large numbers of charcoal fragments, then 2 cm^3 may be too large. As in Mooney & Tinner (2011), it is recommended that a few test samples are completed prior to the main analysis. Often, the organic matter will vary throughout the core. This needs to be taken into consideration when choosing test samples.

The method used in this study is based on the Mooney and Tinner method (2011) with some modifications. To reduce time, the subsamples can be taken using a cut syringe; careful attention should be made to consistency in the bulk measurement as sediment with high quantity of sphagnum moss can be compressed. This can be done by consistency in packing the cut tube. This is less time consuming than volumetric displacement in water for high resolution analysis of long cores.

Disaggregation

Sediment sub-sample of known volume is placed in 10 - 40 ml of cold sodium hexametaphosphate (Calgon) and left overnight. This should be gently mixed to ensure all clumps are disaggregated before rinsing as clumps do not bleach efficiently. The use of a disaggregate may not be necessary on sediments from forest hollows or lake sediments, however using a disaggregation medium can improve efficiency of the bleaching process with compacted peat samples. Rinsing is necessary to remove all of the sodium hexametaphosphate. Further disaggregation may be necessary for dried peat samples; 20 ml of sodium hexametaphosphate combined with 20 ml potassium hydroxide (KOH) followed by 1-2hrs on a hot plate proved to be effective additional process by the author.

Wash 1

Gently wash the sediment through a set of nested sieves (e.g. 125, 250, 500 µm, 1mm) into labeled petri dishes (or beakers if a hot plate is used) with a consistent and minimal amount of water being included. Dividing the sediment into fractions will usually make the bleaching process more controllable and consistent and so aid in removing the organic material. Although this slows down the washing stage, it can quicken the photographic stage. Dividing the sample into two fractions, 125 – 500 µm and > 500 µm can be a useful method. Very few charcoal fragments are usually found > 5 mm in length and many rootlets and other organic pieces can be separated out from smaller fragments. Using the 125 µm sieve instead of the 250 µm sieve can be useful if samples are likely to contain a high amount of grass/dwarf shrubs e.g. *Calluna vulgaris* which tend to be smaller pieces than samples with mainly tree charcoal. This type of vegetation may show a different fire regime than time periods that are forested. 125 – 250 µm is the smallest size fraction that can be identified with a 12 megapixel digital camera although this can be improved with, for example, x12 optical zoom function. The quickest method is to retain one fraction only e.g. >250 µm, however it may mean that longer time is needed on the bleaching process to obtain a consistent bleaching effect.

Bleaching

If there is only a small amount of organic material and no stems or roots, then 0.5 ml of sodium hypochlorite (NaOCl) should be sufficient to remove organic matter in the 125 µm–500 µm fraction and 1 ml for the > 500 µm fraction. However, if the sediment is humified and contains a lot of organic material, then an initial 2 ml and 5 ml respectively of 100% NaOCl should be added to the petri dishes, which should be swirled to aid mixing and then left for a maximum time of overnight in a fume cupboard. For small samples and minimum organic matter, the bleaching time can be as short as ten minutes. A standard range of time would be one to two hours. Further bleach can be added 2ml (or 5 ml at a time for very humified peat) and observed hourly until a clear distinction can be seen between the charcoal fragments and any remaining sediment. The sediment should not be rinsed until the bleaching process is completed. Equal amounts of bleach should ideally be added to every sample; however where there are differences in the type and amount of organic material (more likely to occur if samples are not divided into different fractions), some samples will bleach quicker and need less bleach than others; adding extra bleach in this case is unnecessary and could react with the charcoal fragments reducing them in size. Any roots or stems that remain unbleached and can be identified as such, should be removed from the petri dish after rinsing.

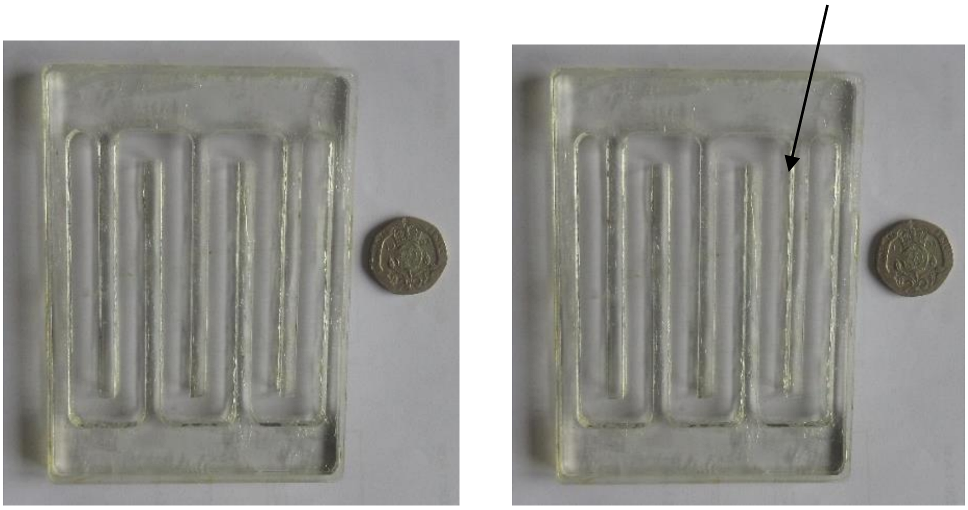
The bleach used here is undiluted sodium hypochlorite (8% active chlorine). Peat samples that are highly humified require a more intense bleaching process than less humified peat to isolate charcoal fragments. The aim is to produce a consistent bleaching effect, and this can be achieved, although care needs to be taken with exposure of the charcoal fragments to the bleach where there is minimal organic material present to avoid damage to the fragments. Where this method differs from Mooney & Tinner (2011) is in the bleaching process as highly humified material requires a more intense process.

Wash 2

Gently wash the sediment through a 125 µm sieve back into the labeled petri dishes. Careful rinsing will minimise fragmentation.

If there is mineral material present in the sample, then many of the larger pieces can be eliminated at the second wash stage. Lighter organic material will float off and heavier mineral matter will tend to sink, although the residue will still need to be checked for charcoal fragments. Larger pieces of organic material can be physically removed with tweezers.

Sphagnum plant parts can form a barrier that blocks charcoal fragments from being seen. If this is the case, then a Bogorov type counting chamber can be used with great success to count charcoal fragments easily and avoid counting any fragments twice. If your laboratory does not have any of these chambers, then unfortunately they are currently relatively expensive to purchase. The chamber was originally designed for counting plankton (Bogorov, 1927; Gannon, 1971) but the design can be adapted for use with macrocharcoal. They can be made quite easily using a laser cutter. Below are images of two chambers that the author made using two pieces of thin Perspex (figure 3-5), the top one was laser cut with channels and the two pieces were then glued together using a flexible, clear drying, waterproof glue. A better method would be to cut the channels into one thicker piece of Perspex.



Channel (glue can be seen at edges)

Figure 3-5: Clear Perspex chamber made by Karen Halsall. The channels are different widths in each chamber.

Visual check

The next step that is recommended is a quick visual check for charcoal fragments using a x 400 magnification lens on a light microscope. If no charcoal fragments are present in the sample, then the process is speeded up as these samples do not need image analysis. Counting the fragments so that you have a general idea of the number present is useful for comparison with the count provided by ImageJ.

Removing non-charcoal material

The extraneous material that makes charcoal identification on the image more difficult can be separated from charcoal fragments in a couple of ways. The charcoal fragments can be pipetted/moved to a clear petri dish containing distilled water out of the Bogorov chamber (Bogorov, 1927) or original petri dish. If you are using a petri dish, then swirling prior to examination under a microscope will move the charcoal to the centre of the dish (and mineral material also). Lighter organic material will generally move to the outside or float. If this is not practical (i.e. too many small charcoal pieces mixed in with non-charcoal material), it may be necessary to take a sub sample. Techniques at the image analysis stage can also be employed to isolate the charcoal fragments prior to taking a photograph. Beetle parts will remain after the bleaching process and need to be removed before taking the image.

3.3.2 *Acquiring a digital image*

Mooney and Tinner (2011) and Mooney and Black (2003) provide excellent advice for this stage. To take a steady photograph, the use of a tripod is recommended. To eliminate shadows, use a good quality light table. A digital camera such as the Canon Ixus (12 x digital zoom function and macro function for taking near images) will produce good enough images. See figures 3-6, 3-7 and 3-8. Make sure you have a scale bar such as a clear ruler and the site name and depth included in the image as in figure 3-6. Alternatively, the site name can be added when the photographs are copied from the camera into a saved file (figures 3.7 and 3.8). It is important to keep the level and type of light consistent for all images as far as possible. Further light can be added if, necessary, by using natural light bulbs above the petri dish. This can be useful to show up coloured non charcoal material. Once the images have been taken, rename the images using the site name and depth.

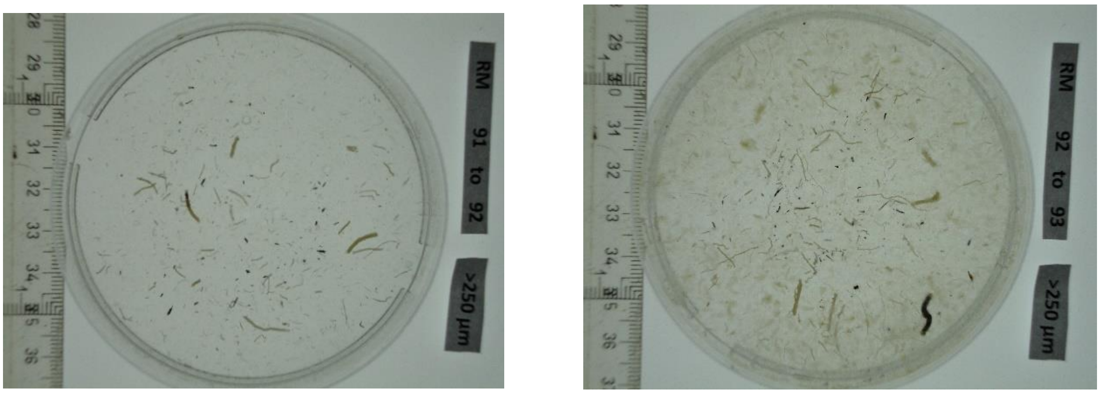


Figure 3-6: Two images of charcoal fragments and organic material.

Figure 3-8: Seeds and dark organic material (depth and site name need to be added).

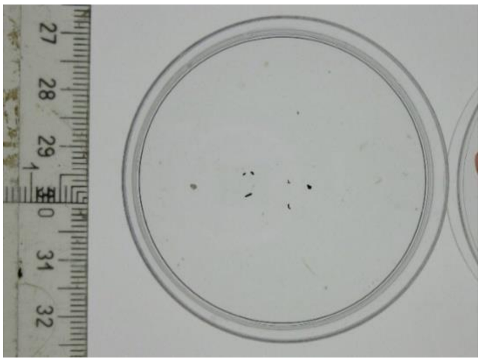
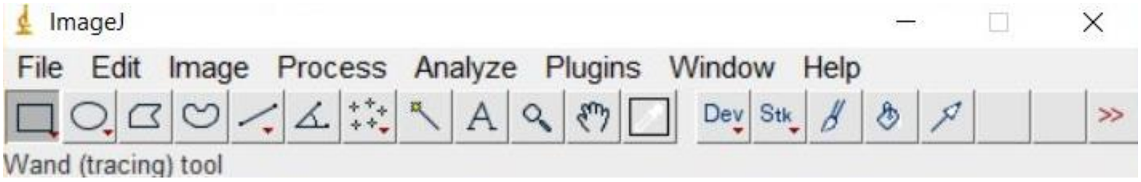


Figure 3-7: Charcoal fragments (depth and site name need to be added).

Digital Analysis

This method was originally adapted from Mooney and Tinner (2011) in combination with Mooney and Black (2003), Scion Image is the recommended analysis programme in these papers, however Scion Image is no longer supported so ImageJ (Abramoff *et al*, 2004) is used in this study. Note that ImageJ removes the need for use of Adobe Photoshop or any other similar image manipulation software.



Wand (tracing) tool

Figure 3-9: ImageJ function bar.

ImageJ can be freely downloaded from http://rsbweb.nih.gov/ij/index.html. The function bar is shown in figure 3-9 and figure 3-10. It can be updated using the help tab. This software is quicker to use than the combined Photoshop / scion Image method and allows for a more refined analysis. It is possible to stack your images and analyse many instantly, however I have not used this method as I have not identified a way to ensure that the same area within which all the charcoal lies is lined up in the same place on every image. Even when the images appear to be similar, slight variations in each photograph lead to inaccuracies that mean the area measurements are incorrect. The author recommends analysing each image separately using a macro for the steps common to each analysis.

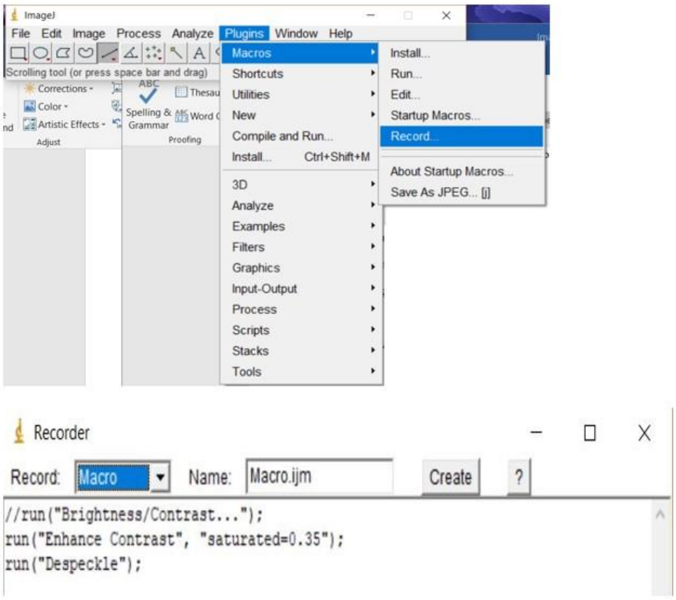
Writing a macro

A macro will enable several general actions to be completed under one script. This can be run for each image.

Open an image that shows charcoal fragments clearly with minimal or no organic matter. Then follow the tabs as shown in step one below.

You can now start writing the general settings that will form the coding for the macro.

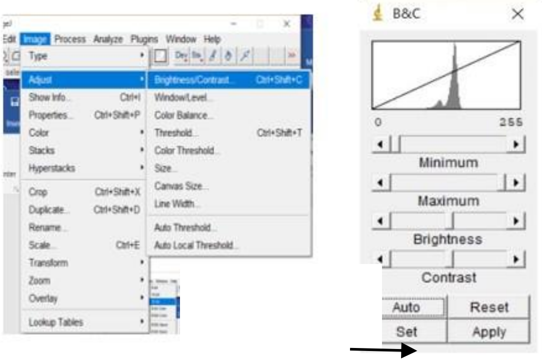
Plugins – macro – record



```
//run("Brightness/Contrast...");
run("Enhance Contrast", "saturated=0.35");
run("Despeckle");
```

Image – Adjust – Brightness/Contrast tabs and select Auto (do not close B & C)

This will optimize each image and adjust for any difference in light whilst photographing the petri dishes.



Process – Noise - Despeckle

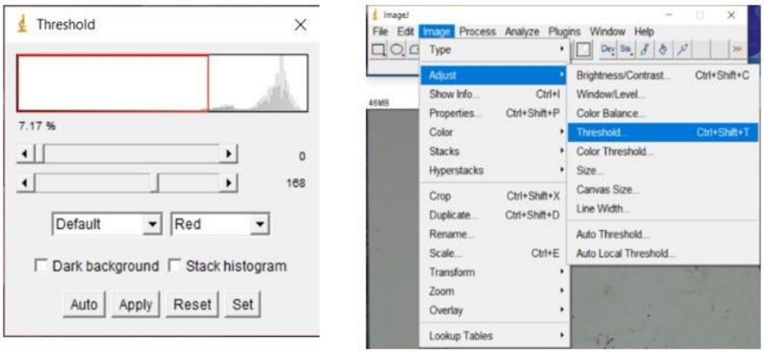
This will clean up the edges of the charcoal fragments and remove noise on the image.

Image – Type – 32 bitmap

Change the JPG image to a bitmap. This is necessary for the threshold tool to work.

Image – Adjust - Threshold

This sets the greyscale level to identify black, opaque charcoal fragments

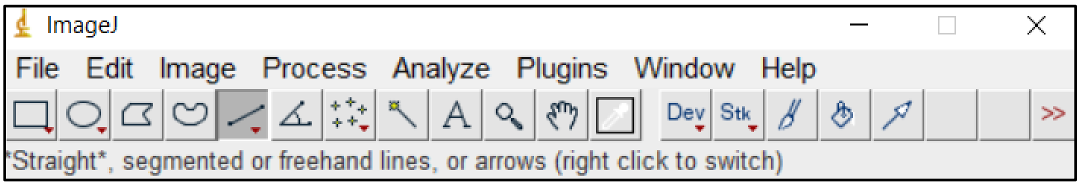


Leaving the lower limit at 0, adjust the upper limit to highlight only charcoal fragments. Use the magnifying glass icon and hand icon to enlarge a fragment and check which pixels are being highlighted. This is a subjective setting and deciding on a value should be practiced using several images before writing the macro, so that the optimum level is set. Any holes in the fragment will be covered by ticking the include holes option on the analyze tab.

Set threshold (don't close Threshold)

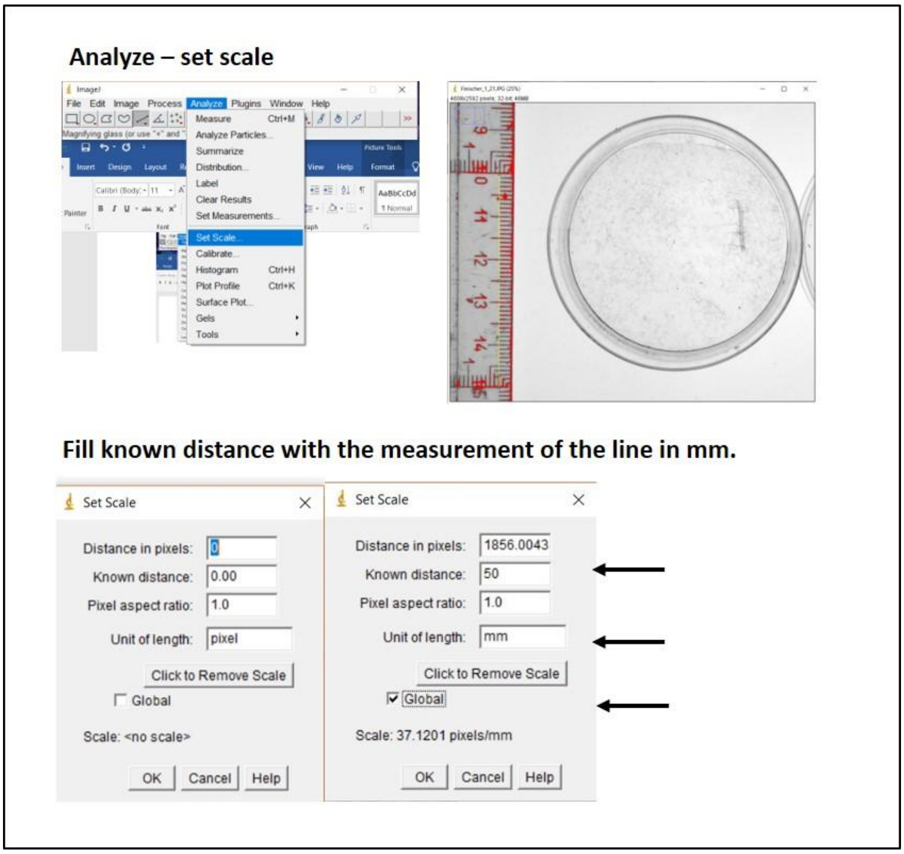
Using the line tool draw a straight line over the ruler on your image for at least 40 mm

This sets the scale of the fragment measurements and the unit as mm. However, you will need to reset this for every image once you have run the macro.



Straight, segmented or freehand lines, or arrows (right click to switch)

Figure 3-10: Image J function bar



Analyze – set scale

Fill known distance with the measurement of the line in mm.

Set Scale

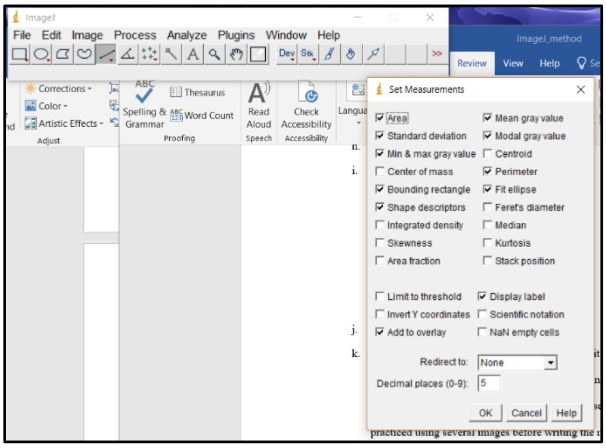
Distance in pixels: 0
Known distance: 0.00
Pixel aspect ratio: 1.0
Unit of length: pixel
Click to Remove Scale
☐ Global
Scale: <no scale>
OK Cancel Help

Set Scale

Distance in pixels: 1856.0043
Known distance: 50
Pixel aspect ratio: 1.0
Unit of length: mm
Click to Remove Scale
☑ Global
Scale: 37.1201 pixels/mm
OK Cancel Help

Change unit of length to mm. Tick global. Click OK

Select Analyze – Set Measurements



Set Measurements

☑ Area ☑ Mean gray value
☑ Standard deviation ☑ Modal gray value
☑ Min & max gray value ☐ Centroid
☐ Center of mass ☑ Perimeter
☑ Bounding rectangle ☑ Fit ellipse
☑ Shape descriptors ☐ Feret's diameter
☐ Integrated density ☐ Median
☐ Skewness ☐ Kurtosis
☐ Area fraction ☐ Stack position

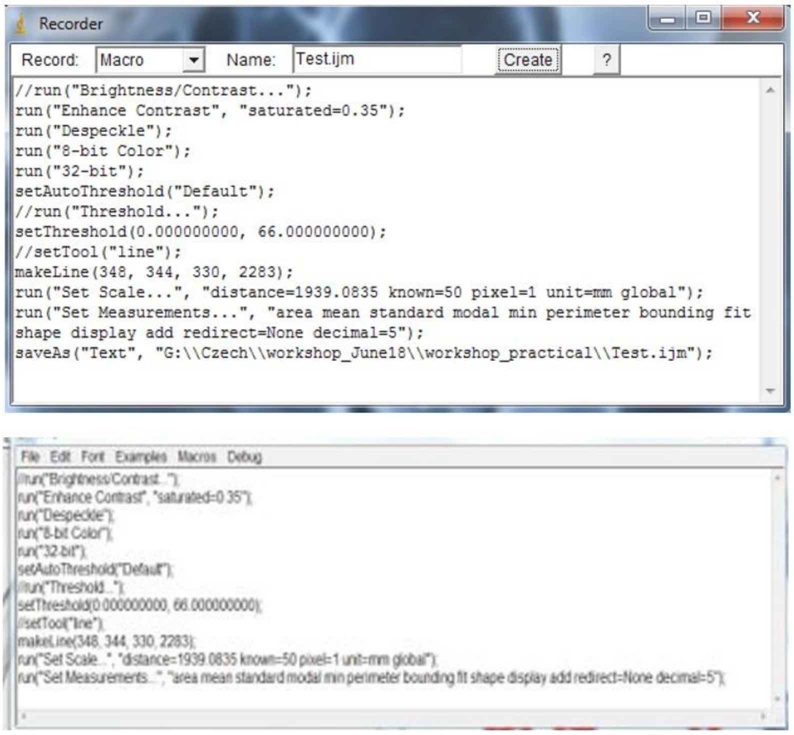
☐ Limit to threshold ☑ Display label
☐ Invert Y coordinates ☐ Scientific notation
☑ Add to overlay ☐ NaN empty cells

Redirect to: None
Decimal places (0-9): 5
OK Cancel Help

Select OK button

Tick the types of data you require. Suggested ones are: Area, Min & Max grey values, Bounding rectangle, Shape descriptors, Mean grey value, Modal grey value, Perimeter, Fit ellipse, Look up the meaning of the different types using the help manual. You will also need Display Label and add to overlay. Change no. of decimal points to required number Change the name of the macro to read (site name).ijm instead of Macro.ijm. It is useful to include the level of the threshold used in the name. Check you do not have any superfluous lines in the text. Remove any lines that are written Close.

Click create



```
//run("Brightness/Contrast...");
run("Enhance Contrast", "saturated=0.35");
run("Despeckle");
run("8-bit Color");
run("32-bit");
setAutoThreshold("Default");
//run("Threshold...");
setThreshold(0.000000000, 66.000000000);
//setTool("line");
makeLine(348, 344, 330, 2283);
run("Set Scale...", "distance=1939.0835 known=50 pixel=1 unit=mm global");
run("Set Measurements...", "area mean standard modal min perimeter bounding fit
shape display add redirect=None decimal=5");
saveAs("Text", "G:\\Czech\\workshop_June18\\workshop_practical\\Test.ijm");
```

```
//run("Brightness/Contrast...");
run("Enhance Contrast", "saturated=0.35");
run("Despeckle");
run("8-bit Color");
run("32-bit");
setAutoThreshold("Default");
//run("Threshold...");
setThreshold(0.000000000, 66.000000000);
//setTool("line");
makeLine(348, 344, 330, 2283);
run("Set Scale...", "distance=1939.0835 known=50 pixel=1 unit=mm global");
run("Set Measurements...", "area mean standard modal min perimeter bounding fit shape display add redirect=None decimal=5");
```

File – save as

Save the macro to a convenient folder. E.g. in your folder of images

Close image without saving changes. Click No.

Save changes to "Fleischer_1_21.JPG"?

Now close the Threshold and B & C boxes

Analyse images

Install and run the macro to perform these general actions. You will still need to reset the scale for each image. Using the **Plugin – Macro-Install** tabs, find and install your pre-prepared macro. Open your first image. Next run the macro by clicking on it. (**Plugins – Macros - name of macro)**

Check that the paintbrush tool is present on the icon menu. If not, add it using the arrow tab at the RHS.

Open a second view of the image and keep as a colour image.

Use the paintbrush tool and the colour image as a reference, paint out any organic matter that will fall within your region of interest that could be mistakenly identified by the software to be charcoal.

Check that the line that is present on the ruler represents the known length and if not adjust the table under the **Analyze - Set Scale** tabs.

Use the **oval, polygon or freehand tool** to draw around your charcoal images, excluding non-charcoal material where possible.

You could use **Edit-Clear Outside** if you wish to remove all other parts of the image except the region of interest (ROI).

Analyse - Analyse Particles

You can eliminate unwanted small fragments by setting the size box to **0.002 – Infinity**.

Tick the boxes; Display Results; Summarize; Include Holes; Add to Manager. Make sure Clear results is not ticked. Click OK.

The Add to Manager box will show the number label for each fragment. You need to **discard the results in the ROI** table after each analysis otherwise all previous numbers are retained with a new image.

Save Results and Summary data every 10 samples (for example) into a folder. Alternatively copy and paste the results directly onto an excel spreadsheet. The summary data is useful as a total area for each sample is calculated.

Fragment	Area	Mean	Perim.	Width	Height	Major	Minor	Circ.	AR	Round	Solidity
1	0.0218	38.6666	0.5044	0.1616	0.1616	0.1759	0.1576	1	1.116	0.896	0.9231
2	0.008	29.8182	0.3206	0.1078	0.1077	0.1214	0.0837	0.9762	1.4505	0.6894	0.8462
3	0.0021	49.4444	0.1524	0.0539	0.0539	0.0637	0.0435	1	1.4639	0.6831	0.8571
4	0.00583	54	0.35939	0.10798	0.13497	0.16493	0.045	0.56715	3.665	0.2729	0.7273

Table 3.4: An example of the measurements for each charcoal fragment that is available using ImageJ.

3.4 Results

The effect of sodium hypochlorite on fossil charcoal was tested over a 24 hr. period on a single large piece of fossil charcoal (figure 3-11). The charcoal fragment had already been processed with bleach however, the results still show the effect of bleach on charcoal fragments if left in the bleach for 24 hours. Table 3.10 shows that the charcoal fragment increases in area as the time increases. Eventually, the fragment breaks down into several pieces. The smaller pieces disintegrate until one large piece is left (figure 3-12).

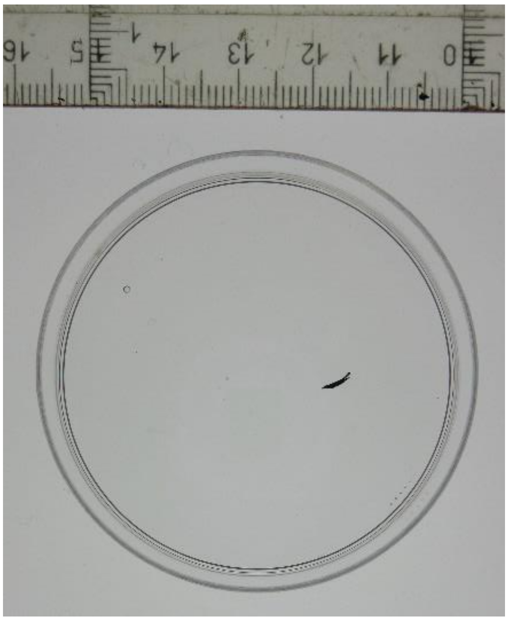


Figure 3-11: Image of charcoal fragment prior to adding sodium hypochlorite.

Time	Area 1	Area 2	Area 3	Perim 1	Perim 2	Perm 3
0	1.93	1.92	1.91	11.31	11.29	11.27
12:10	1.88	1.88	1.88	10.88	10.89	10.88
13:10	2.31	2.31	2.31	13.03	13.03	13.05
14:15	2.38	2.38	2.98	13.53	13.58	15.2
16:15	2.77	2.77	2.77	7.41	7.41	7.41
17:15	2.83	2.82	2.82	7.38	7.36	7.36
24 hrs	3.21	3.19	3.21	2.4	2.4	2.4
48 hrs	2.19	2.2	2.2	10.28	10.33	10.31

Table 3-2: Results for bleach test over 48 hours.

Time elapsed		mean area	
hrs	**mins**	**mm²**	
0		1.92	
1		1.88	
2	**5**	2.58	
4	**5**	2.77	
5	**5**	2.82	
24		3.2	broken (several pieces)
48		2.2	one piece only

Table 3-3: Mean area for each time period (three areas calculated).

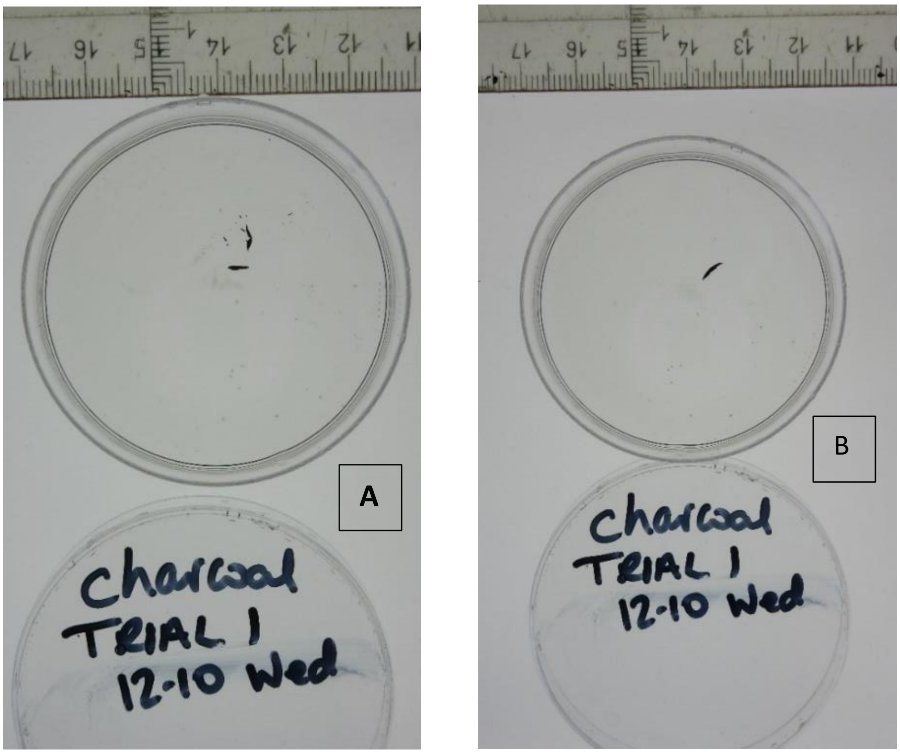


Figure 3-12: Images of charcoal fragments used in the trial; After 24 hrs (A), after 48 hrs (B).

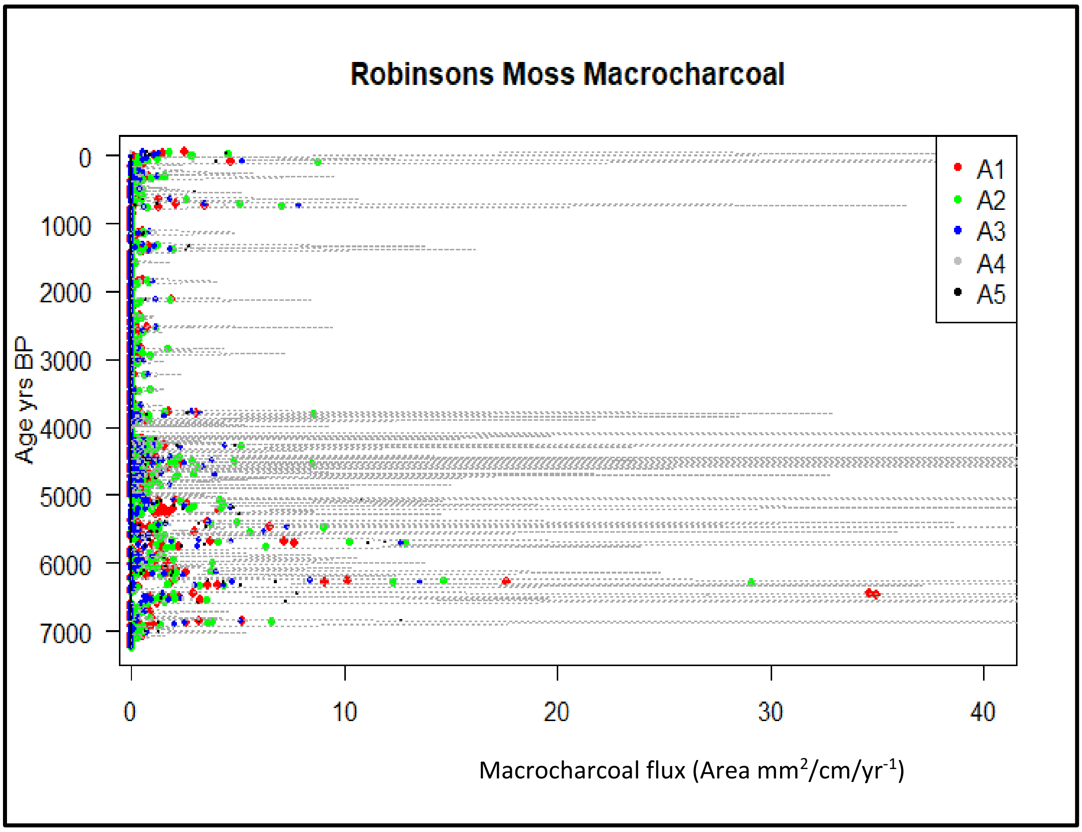


Figure 3-13: Charcoal Area flux (grey dotted line) plotted with charcoal fragments divided into five fractions at each cm depth (A1 = 0.18 – 0.5; A2 = 0.5 – 1; A3 = 1 – 1.5; A4 = 1.5 – 2; A5 = >2 mm).

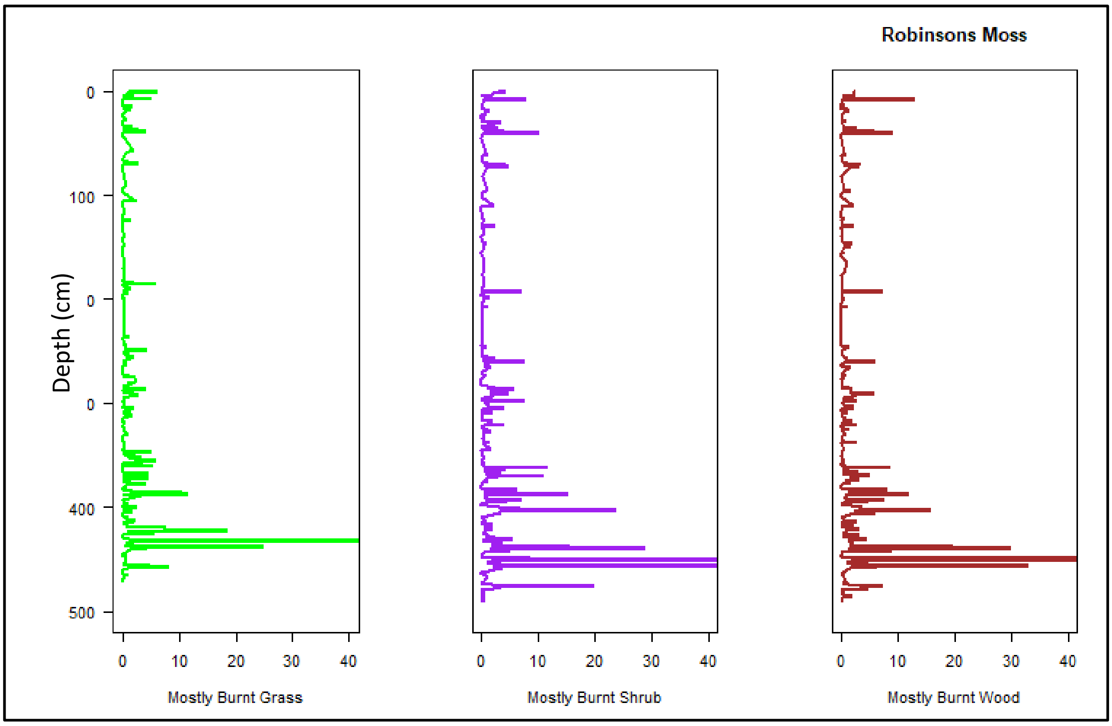


Figure 3-14: Charcoal fragments Area divided into three categories using the ratio Width/Height (AR), Mostly burnt Grass: AR = 0 - 0.5 (green) line); Mostly Burnt Shrub AR = >0.5 – 0.75 (purple line); Mostly Burnt Wood AR = >0.75 - 1 (brown line) plotted against depth (cm).

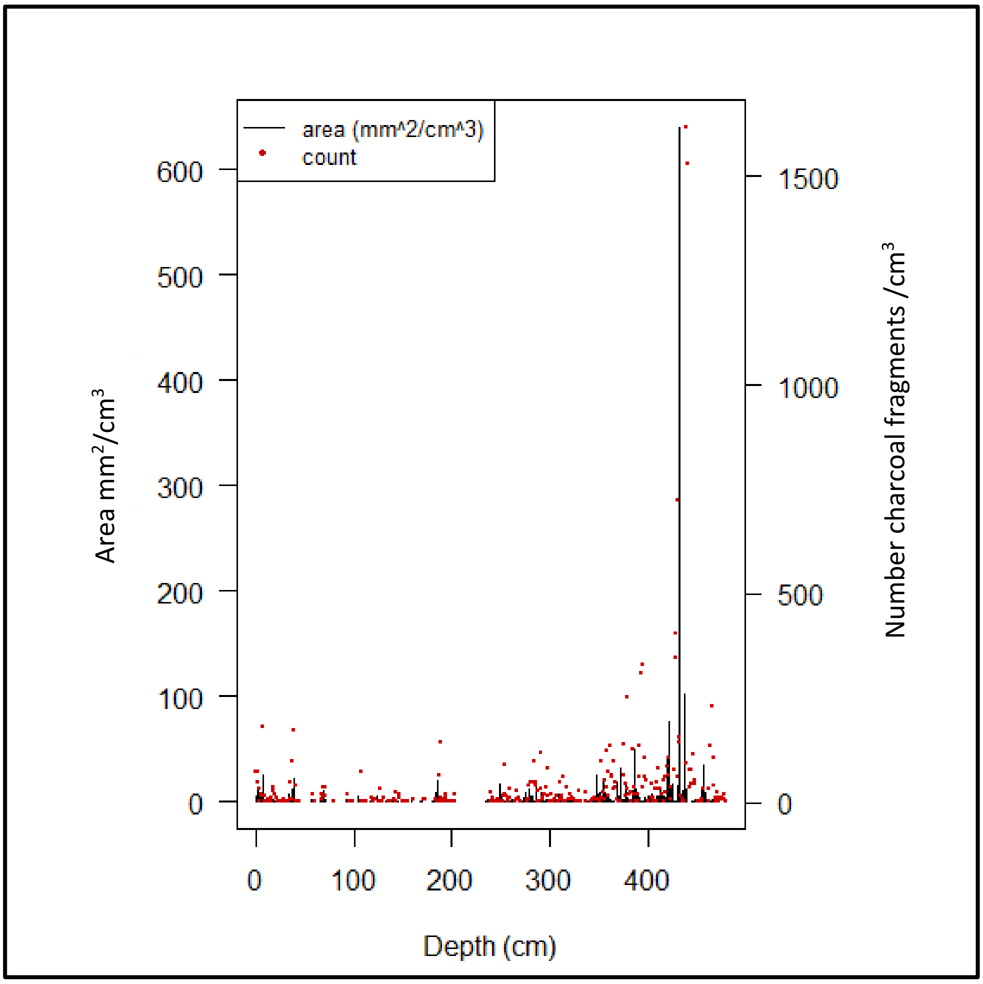


Figure 3-15: Robinsons Moss: Charcoal fragment area (mm^2/cm^3) plotted with charcoal fragment count (number/cm^3) against depth (cm).

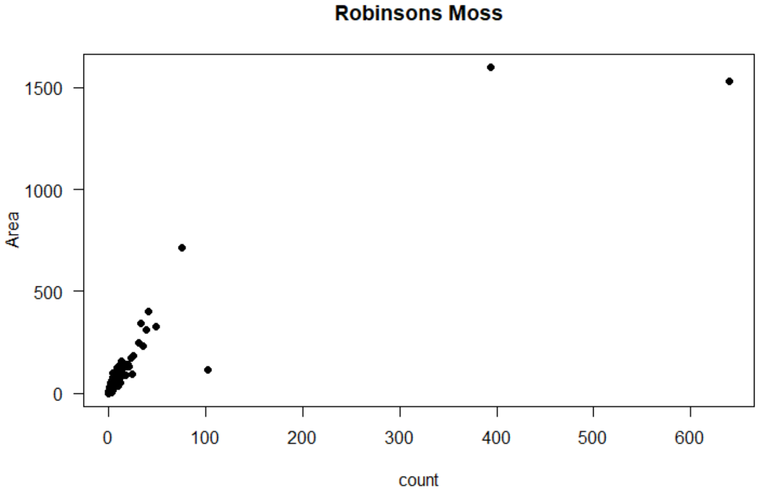


Figure 3-16: Scatter plot showing correlation between fragment particle Count / cm^3 and Area (mm^2/cm^2).

3.5 Discussion

Image analysis is a semi-automatic method of isolating and quantifying macroscopic charcoal fragments within sedimentary deposits. Figures 3-13 to 3-16 show some of the ways that the measurements for individual charcoal fragments can be analysed. There are several aspects of using this method of image analysis for macroscopic charcoal fragments that merit discussion such as sample volume, mesh size and fraction size included in the final analysis. Currently, these aspects are chosen by the researcher to suit the method and type of sediment. Often the issue is time; the author has shown here the level of detail available that can be obtained using this method and so recommends it to charcoal analysts. Other faster image analysis techniques using image manipulation to remove non charcoal particles can be useful but there is often some loss in accuracy that occurs during the process of photograph manipulation.

Using nested sieves of mesh size 250 µm and 1 mm for peat bogs and a mesh size of 125 µm for lake sediments can be a useful guide although different sediments contain different types of vegetation and mineral matter so this cannot be a hard and fast rule. The ultimate object of image analysis is to have an image that only contains charcoal fragments. The method in this study describes a relatively quick route to physical removal of non charcoal fragments and so provides accurate results in terms of area measurements.

Increasing sediment volume increases the probability of obtaining a good fire record, however this increase the time taken for processing so a compromise decision is usually made between these two aspects.

Usually all fraction sizes are included within charcoal fragment analysis, however, using this method, we can start to explore the relationship between fragment morphology and the type of burnt vegetation. This is explored further in subsequent chapters. Aspects of this method are explored below.

1 Large sub-samples can be analysed.

Using large sub samples increases the processing time but can improve the statistical error caused by variation in fragment abundance within a core. For this study, the sub sample volumes were between two and three cm^3 (water displacement method). Carcaillet recommended using 3 cm^3 (Carcaillet *et al*, 2001) however this sample size may be too onerous to analyse depending upon the number of charcoal fragments and other organic material so a compromise may need to be taken between sample volume and time available.

2 Contiguous high resolution samples can be analysed relatively quickly.

Using ImageJ, repeat measurements for each sample can be quickly executed especially if a macro is used. The total area of charcoal fragments mm^2/cm^3 can be calculated by dividing the area value by the volumetric measurement and can be easily be converted to charcoal influx using the sedimentation rate obtained from radiocarbon dates to get influx $mm^2/cm^2/yr$.

3 Clearer images are better but can add time to the process.

If extraneous material is not removed prior to taking the image, then there are several other actions described in this method that will remove non charcoal fragments from the analysis. These are described below.

The threshold value can usually be set to be consistent down the core and between cores. Charcoal has been identified in this study to lie within a range of values between 50 and 80 greyscale values (no units). Other parameters are also repeatable e.g. brightness and contrast values.

After the bleaching process, large pieces of dark organic material can be identified using a low magnification microscope and eliminated using a pipette, micro spatula or soft tweezers. Charcoal fragments can often be photographed in isolation, even from highly organic, compacted sediment and this method is less subjective than just visual identification of charcoal. Use of this method can increase the accuracy of calibration across sites.

Most of the mineral matter within samples can be eliminated at the sieving stage by a flotation method due to differences in weight between lighter organic material and heavier mineral pieces.

4 Quantification using count and area of charcoal fragments.

As previously discussed, the unit of measurement varies between studies. For macrocharcoal, count or area is often used. The use of area removes the overestimation caused by fragmentation of particles due to taphonomic processes. Area and count data for Robinsons Moss is shown in figure 3-15. The correlation value for the Robinsons Moss data using Kendall’s tau for non-parametric distributions between abundance of fragments and area of fragments is 0.627 with a p value of $2.2e^{-16}$ (figure 3-16). There is some significant correlation, but the tau value is not high (maximum correlation would be a value of one). Other studies show correlation between area and count (Tinner *al*, 1998; Finsinger, 2008) for lacustrine sediments and many fire studies use only counts as a method of quantification. Using this method, both area and count are available for use as a quantification unit. It is shown in chapter four that not all fraction sizes correlate in terms of quantity between cores taken at different parts of a bog (e.g. edge and centre); Finsinger (2014) showed that fragmentation is an issue for Mediterranean forests. Hence the use of count per se as a quantification method needs to take the position of the core within the deposition site into consideration when compiling datasets from peat bogs (Halsall, 2018), as well as the ecology of the site.

The accuracy of using area as a quantification method obtained from image analysis can depend on the presence or absence of extraneous organic matter captured within the image. With only charcoal on the image, the threshold value can be maximised whereas if dark oxidised material or mineral material is present on the image, then the area might be reduced if the threshold value is reduced to ensure that non-charcoal material is not included in the analysis. Also, under a lower threshold limit, the programme may split fragments into more than one particle which would erroneously increase the count. Under these circumstances, the count should be checked for accuracy. The best results are obtained if only charcoal fragments are present on the petri dish.

5 Images are easy to store and the analysis is repeatable.

Images of petri dishes can be stored and transferred to other researchers for repeat analysis or inclusion in other studies for the same location or in compilation of studies using the same method. The results obtained from the ImageJ programme are easily transferred to an Excel document for further numerical manipulation and plotting of pollen/charcoal fragment correlation plots and vegetation response curves.

6 Other organic material can also be quantified such as fungal spores released from mycorrhizae.

Native tree taxa that are associated with fungal mycorrhizae that produce spores include *Pinus sylvestris*, *Betula., Quercus, Salix.* Fungal mycorrhizae are also associated with Heather spp. and *Vaccinium myrtillus*. These are easily identifiable both under the microscope and on images. They can be separated from charcoal material using the data for circularity when circ. is ticked on the Measurement tab.

7 The method can be extremely quick to use if there are only charcoal fragments present in the image.

Quick analysis can be achieved using the techniques described in this chapter. Despite needing extra time to remove other dark organic or mineral material to obtain clear images, it is time well spent as the area measurements obtained for each charcoal fragment are obtained using ImageJ easily and quickly. Both area and count are available; area as a quantification unit has advantages over count, particularly for lacustrine sediments where fragmentation can be an issue (Leys *et al*, 2013).

8 Class sizes

Using this method, charcoal fragments can be divided into any number of class sizes to match other data sets and correlations between class sizes can be calculated. Figure 3-13 shows macroscopic charcoal fragment area values for Robinsons Moss, divided into five class sizes: A1 = 0.18 – 0.5; A2 = 0.5 – 1; A3 = 1 – 1.5; A4 = 1.5 – 2; A5 = >2 mm. Although it is difficult to see the ratio of each class size in each sample when the fragments are shown in one graph. Clearer graphs are shown in chapter four where these class sizes are used to compare two methods for macrocharcoal analysis.

9 Aspect ratio

Results for individual charcoal fragments can be analysed for the types of vegetation burnt. The morphology of charcoal fragments has been explored in various papers such as Umbanhower & McGrath (1998) and Jensen (2007), where wood, grass and leaves were shown to display different morphological types. This difference can also be described by the ratio of width to length (W/L). This ratio may serve as a useful indicator of the type of vegetation burnt (Jensen, 2007). Results from the analysis of Robinsons Moss are shown in figures 3-13 and 3-14 where fragments have been divided into three classes using the W/L aspect ratio (0 – 0.5; 0.5-0.75, 0.75-1). The middle class (0.5-0.75) has been denoted shrub although it is of unknow morphological type. It could be an indicator of shrub taxa or alternatively could also be a category that is showing burnt leaves (Jensen, 2007)).

10 Use of sodium hypochlorite as a bleaching agent

The strength and quantity of bleach used varies between researchers. It can be diluted depending on the sediment volume and the amount of organic material on the Petri dish.

Here, the author has tested various concentrations of sodium hypochlorite and found that the effect can be controlled by dividing the sub sample into fractions and by limiting the time that the sediment remains in the bleach solution. Full strength bleach is used; however, each petri dish contains a similar amount of distilled water. The effect of the bleaching agent was tested, and the results can be seen in table 3-2. Table 3-3 shows the mean value calculated using 3 repeated result measurements.

Chapter 4 Fossil charcoal quantification using manual and image analysis approaches

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4.1 Abstract

Charcoal particles are evidence of past fire events and macrocharcoal particles have been shown to represent local fire events. There are several methods for the preparation and quantification of macro-charcoal particles, none of which have been universally accepted as standard. Very few studies compare methodological differences and no studies to date compare quantification by mass with quantification by volume using image analysis. Using three cores taken from a peatland located in SE Norway, we compare these two established methods using a generalized linear mixed model (GLMM) and a split-plot ANOVA test. We show that charcoal volume (image analysis method) was a better predictor of charcoal mass than charcoal particle number and the same size classes of charcoal as size class distributions were not spatially and temporally correlated. Although there is still a need for a common and unifying method, our results show that quantification of charcoal particles by image analysis including size (e.g. height in mm) and area (mm^2) /volume (mm^3) measurements provides more significant results in cross site or multiple site studies than quantifications based on particle number. This has implications for the interpretation of charcoal data from regional studies that are used to model drivers of wildfire activity and environmental change in boreal – temperate landscapes during the Holocene.

Key words

Charcoal analysis, charcoal area-volume relationships, charcoal mass, charcoal particle number, image analysis

4.2 Introduction

Recurring wildfire is a key-disturbance agent that has been a major driver of forest evolution and development worldwide. Every fire event produces and distributes pyrogenic organic matter, of which charcoal is a main component when woody biomass burns. As charcoal remains in soils and sediments for centuries (Scott, 2010) its record represents a significant carbon pool and a legacy of spatial and temporal patterns in wildfire activity that plays an important role in the global terrestrial carbon cycle. However, it is far from simple to quantify and interpret the charcoal record, and a multitude of methods and interpretations have been used in order to estimate past patterns in fire activity. Actually, there are over 120 separate approaches used for identifying and quantifying charred remains in the Global Charcoal Database (http://www.paleofire.org/), including particle counts, point counts, area measurements, chemical assays, and estimates of influx, concentration, dry mass and reflectance (Power *et al*, 2010).

The approaches used for recording charcoal in soil and sediments fall into three distinct groups: (a) manual data collection with subjective decisions made on the identification of dark objects as charcoal, for example, point counts (Clark, 1982) and dry mass determination (Ohlson et al, 2009); (b) data derived from more automated systems of analysis that may permit some human intervention (e.g. image analysis) (Mooney and Black, 2003; Mooney and Radford, 2001; Mooney and Tinner, 2011); and (c) a broad range of chemical assays, which have been shown to render different and assay-specific results (Hammes *et al*, 2008; Quenea et al, 2006). In addition, there is also a great diversity of methods used for analysis, standardization and presentation of charcoal data and this is an active research area with a widespread use of the CHAR (charcoal accumulation rate) approach for data standardization (Finsinger et al, 2014; Hawthorne and Mitchell, 2016; Leys et al, 2013). CHAR is based on the principle that peaks in charcoal fragments represent local fire events (Higuera et al, 2007; Olsson et al, 2010) but the data also contain ‘noise’ (random variability) and that separating samples in a detrended CHAR time series into two distinct populations – signal (S) comprising samples above a set threshold and noise (N) the remaining samples at or below the threshold – will identify the peak series

(Higuera et al, 2011; Kelly et al, 2011). In contrast, data collection methodological issues have received relatively less attention, although Schlachter and Horn (2010) found that abundance of charred particles in lacustrine sediment samples were significantly reduced with increasing strengths of hydrogen peroxide (widely used as a pre-treatment for image analysis of charcoal samples). Schlachter and Horn (2010) also used horizontally adjacent and replicated samples in their study to call attention to the issues of sample volume and spatial variation. Multiple core studies and within core study comparisons are rarely done in palaeoecological research, which generally has been based on the analysis of a 'single core sample' (Higuera et al, 2005; Ohlson et al, 2006). There is thus a general lack of knowledge about how much charcoal records may vary in terms of particle number and size across fine spatial scales in a given biological archive such as, for example, a peat-basin. There have also been investigations of how the choice of study units impacts on the estimates of charcoal abundance. Charcoal particle to number–area–volume relationships have been of particular concern in these investigations (Ali et al, 2009; Crawford and Belcher, 2016; Leys et al, 2013; Weng, 2005). A main conclusion from these investigations is that area and volume estimates are more accurate and robust to depict the amount of charcoal than particle number, which can be significantly influenced by both taphonomic and laboratory processes. However, to the best of our knowledge, no studies have examined how charcoal particle number, area and volume relate to charcoal mass in a given charcoal record. The mass unit is particularly important and interesting in this context as it is notoriously time-consuming and costly to estimate charcoal mass in soil or sediment samples (Crawford and Belcher, 2016; Hammes *et al*, 2008; Ohlson et al, 2009; Schmidt and Noack, 2000). Statistically significant relationships between data for charcoal mass and charcoal data derived from semi-automated and objective approaches (e.g. image analysis) will thus open up opportunities for time-efficient and precise quantifications of charcoal in a given sample, which in turn has the potential to be a powerful tool to improve our knowledge about the size of the charcoal pool in terrestrial soils as well as in aquatic and marine sediments.

In this paper, we compare a robust manual method of charcoal particle number and mass estimation with a semi-automated image analysis system that records particle number, shape and size, which in turn have been used to calculate particle area and volume. To do this, we use duplicate sub-samples from three peat cores. First, we assess how well the manual and the image analysis methods accord in estimations of charcoal particle number in different size classes and then assess which variables from the image analysis can best explain charcoal mass in a given sample of peat. Moreover, as the three peat cores were collected from the same basin in close proximity to each other, we have also been able to explore horizontal variations in charcoal particle number and size at a fine spatial scale covering different distances from the border of the peat deposit.

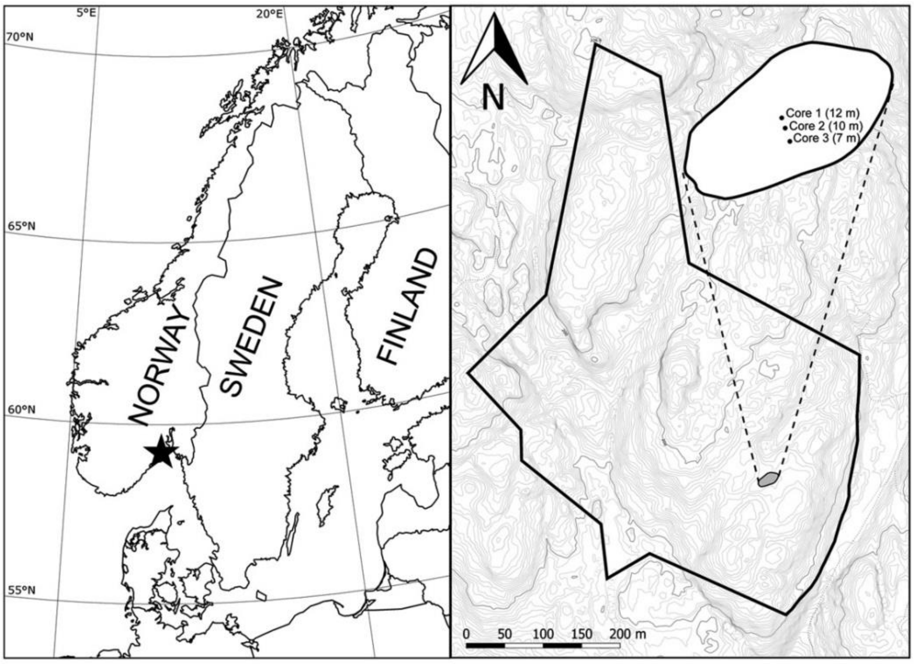

Figure 4-1 National location of the study site in SE Norway (left). Brånakollane Nature Reserve (right) with the peatland marked in grey. The coring positions within the peatland and their distances from the border are shown in the insert. Topographic contour line distance =1m.

4.3 Material and methods

4.3.1 *Study site*

Our study site, which is a peatland, is located in Brånakollane Nature Reserve (59°20’ N; 10°06’ E) about 15 km north of the town of Larvik in SE Norway in the Oslo rift geological area (Figure 4-1). Brånakollane is characterized by a natural beech (*Fagus sylvatica*) forest covering about 20 ha. Norway spruce (*Picea abies*) forests surround the forest reserve, and the border between the beech and spruce forest is very sharp and distinct. The forest floor vegetation is generally sparse, particularly under the beech canopy, and consists mainly of *Oxalis acetosella, Anemone nemorosa, Deschampsia flexuosa, Festuca altissima, Poa nemoralis* and *Dryopteris* ferns.

The peatland under study is a small hollow and is located in the SE part of the nature reserve. The border between the peatland and surrounding beech forest is sharp due to steep slopes, which makes the peatland basin well defined. The peatland is rather wet and its hydrology is driven by an inflow of seeping water from the surrounding slopes, although there is no distinct in- and outflow of water through channels. Only a few, small beech saplings grew on the site and the surface vegetation was sparse due to abundant occurrence of beech leaf litter. Forest species have dominated the Brånakollane region since 12,000 cal. year BP (Figure 5 in Bjune et al, 2013). The largest change in the local forest vegetation occurred around 1350 cal. year BP where there was a shift from a diverse landscape with broad-leaved trees to a less diverse landscape with *Fagus sylvatica* and *Picea abies* (Bjune et al, 2013). Detailed information about site conditions and vegetation history are available in Ohlson et al. (2017), Asplund et al. (2015) and Bjune et al. (2013).

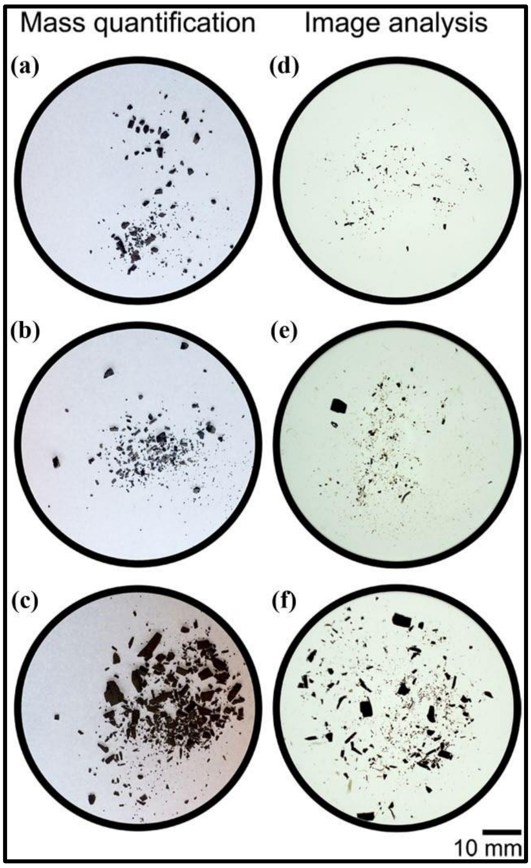

Figure 4-2: Charcoal appearance in three peat samples as determined by (a, b and c) the mass quantification method and (d, e and f) the image analysis method.

4.3.2 *Peat sampling*

Three peat cores were collected using a Russian peat corer (50 cm core length and diameter 5 cm) in June 2014. All cores included the entire peat column from the peatland surface down to the underlying mineral soil. The coring positions were selected to cover a gradient from the central and deepest part of the peatland towards its border. The distance between the central position and the border was approximately 12 m and the total distance among the three positions was 5 m (Figure 4.1, insert top-right).

Charcoal bands were identified in the field immediately after the cores had been extracted and only these bands were sampled in the field by cutting 1-cm thick peat slices with a sharp knife (see Ohlson et al, 2006). There were 12, 21 and 12 slices from cores 1, 2 and 3, respectively (distances from peatland margin are 12 m, 10 m and 7 m, respectively). Each slice was cut in two equal-sized parts (~5 cm3) and then stored in a labelled zip-lock plastic bag. The samples were stored frozen before analysis. By using this approach, we have most likely overlooked peat sections with small amounts of charcoal that was not visible by the naked eye in the field.

4.3.3 *Charcoal analyses*

One part of each sample slice was analysed at the Norwegian University of Life Sciences for content of macroscopic charcoal by hand picking (see Figure 4-2 a–c) as described by Ohlson et al. (2009). By using a stereo microscope with a measure scale, the particles were categorized in five size classes (1 = 0.2–0.49; 2 = 0.5–0.99; 3 = 1.0–1.49; 4 = 1.5–2.0; and 5 = >2.0 mm) and the number of particles were determined for each size class. After the number of particles were determined, they were dried at 70°C and their total mass was determined (g cm–3). This approach is from now on referred to as the mass quantification method.

The second part of each slice was analysed at the University of Liverpool. Each sample was left overnight in 20 ml Calgon (7 g of sodium carbonate (NaCO3) and 33 g of sodium hexametaphospate (Na(PO3)6) dissolved in 1 L of double distilled water), then gently washed through a 250 µm sieve. The retained sediment was washed into petri dishes and 5 ml pure sodium hypochlorite was added. The samples were then left to bleach overnight and rewashed using a 125 µm sieve to capture broken fragments. An extra 1 ml sodium hypochlorite was added to samples that were rich in organic material to ensure a similar colour reduction for all samples (sodium hypochlorite works by using free chlorine molecules which reduce in effect over time). Measurements of charcoal particle counts were recorded using ImageJ (Abràmoff et al, 2004; Schneider et al, 2012). Figure 4-2 shows examples of the images used in ImageJ and for comparison, images of the charcoal used in the mass quantification method. The images were despeckled, adjusted to auto brightness/contrast and then converted to 32 bit greyscale images. A threshold of 75 greyscale units was used for core one and a threshold of 50 greyscale units for cores two and 3#three apart from four samples for which a greyscale threshold of 184 was used as the charcoal fragments were very small and faint. Charcoal particles >20 µm2 were recorded. Three samples were characterized by large amounts of small charcoal fragments and dark mineral material, which made it necessary to divide these into smaller portions to exclude non-charcoal material with precision. Charcoal particle aspect ratio (AR) was recorded as minor axis/major axis of the fitted ellipse and also as the ratio of width / height for a fitted rectangle, which in turn were used to calculate particle area (mm^2. Cm^{-3}). This was converted to particle volume ($mm^3.cm^{-3}$) based on Weng's equation (Weng, 2005), with the assumption that the type of burnt vegetation was similar throughout the core, so C = 1:

$$V_i = C \sum_{i=1}^{N} A_i^{\frac{3}{2}}$$

where V1 = total volume; Ci = coefficient for particle #i; Ai = area of particle #i.

The Holocene vegetation history for Brånakollane is consistently dominated by forest (see site description) so the assumption that C = 1 is valid. From now on, this approach will be referred to as the image analysis method. The explanatory variables from the image analysis method that we use in the statistical analyses for each sample are particle number for each size class, total number of particles, particle volume for each size class and total particle volume. Particle volume is auto-correlated with particle AR and area (spatially scaled as mm^2) as the volume is calculated directly from these variables, which imply that it is not meaningful to include AR and area variables in the statistical analyses.

4.3.4 *Statistical analyses*

Charcoal particle distributions were strongly right-skewed and we performed a generalized mixed model (GLMM) using the function glmer.nb in the R-package lme4 (Bates et al, 2015), assuming a negative binomial distribution, to test the effect of method (mass quantification vs image analysis), peat core position and particle size class on number of charcoal particles. Sample ID was used as random factor. To test the effect of method and peat core position on the proportional distribution of charcoal particles, we used a split-plot ANOVA. Here, normality assumptions were met by log transformation. We used a split-plot ANOVA to test for the effect of method and core sample on the proportion of particles in size class five. As the raw data were strongly right-skewed and did not meet normality assumptions, we have used the non-parametric Spearman rank correlation to estimate the relationship between charcoal mass data and the image analysis variables.

Particle size class	Core 1		Core 2		Core 3	
	Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
1	2.3 ± 0.7^{a}	4.1 ± 3.1^{a}	2.8 ± 0,7^{a}	13.5 ± 10.0^{a}	7.5 ± 2.2^{a}	76.7 ± 6.5^{b}
2	1.7 ± 0.7^{a}	2.8 ± 2.1^{a}	1.8 ± 0.4^{a}	5.7 ± 3.4^{a}	3.8 ± 1.1^{a}	34.2 ± 3.6^{b}
3	1.3 ± 0.5^{a}	0.9 ± 0.7^{a}	1.1 ± 0.2^{a}	1.4 ± 0.8^{a}	2.0 ± 0.5^{a}	7.8 ± 2.5^{b}
4	0.9 ± 0.3^{a}	0.3 ± 0.2^{a}	0.6 ± 0.2^{a}	0.4 ± 0.2^{a}	2.2 ± 0.7^{a}	2.8 ± 0.9^{a}
5	0.5 ± 0.2^{a}	0.3 ± 0.2^{a}	0.7 ± 0.2^{a}	0.3 ± 0.1^{a}	3.9 ± 1.0^{a}	4.8 ± 1.9^{a}
Total number	6.7 ± 2.3^{a}	8.3 ± 6.3^{a}	7.1 ± 1.2^{a}	21.3 ± 14.4^{b}	19.4 ± 5.1^{a}	126.3 ± 2.9^{b}

GLMM: generalised linear mixed model.

Table 4-1: Charcoal particle number (mean ± 1 SE cm–3) in different size classes from charcoal bands in three neighbouring peat cores collected at different distances from the border of the peat basin. Particle number was estimated by two different methods, where method one is a mass quantification method based on manual hand picking, and method two is based on image analysis; see ‘Material and methods’ for further information. Core one was collected in the centre of the peat basin and core 3 was collected closest to the basin border. The distance between cores one and two was ca. 2 m, and the distance between cores 2 and 3 was ca. 3 m. Different letters for Methods one and two within a given core indicate significant difference (GLMM; $p < 0.05$; Tukey test – also see Tables 4.5 and 4.6.

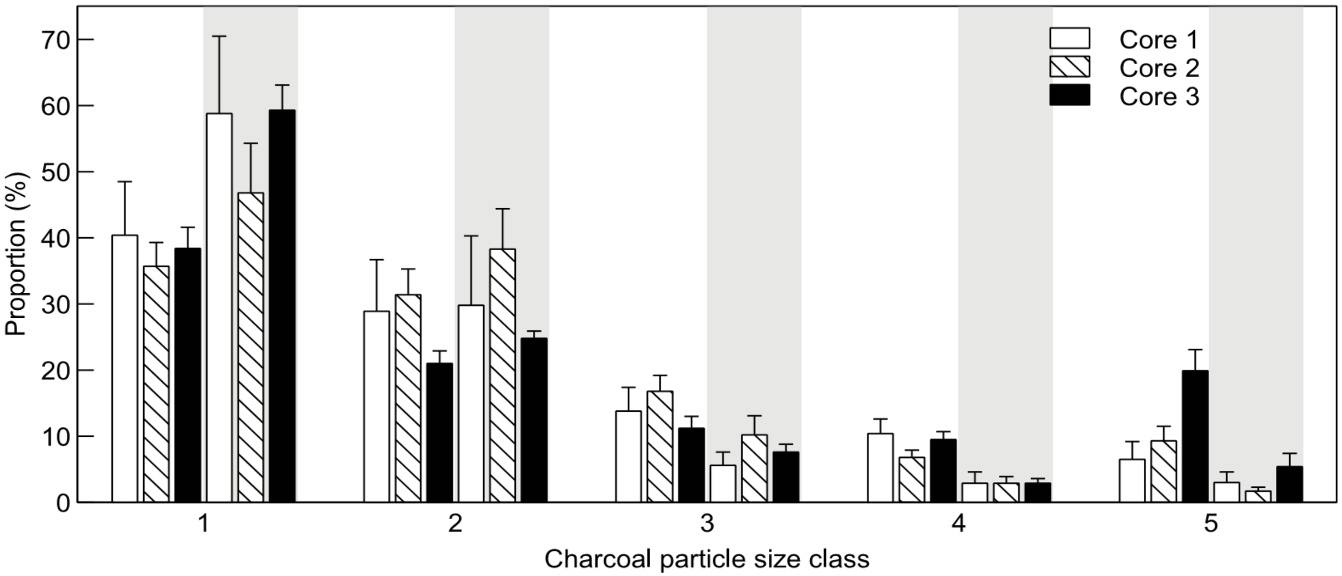

Figure 4-3: Proportion of charcoal particles in different size classes from three neighbouring peat cores as estimated by two different methods. Light-grey-shaded proportions were estimated by automated image analysis and the unshaded proportions w estimated by manual hand picking; see 'Material and methods' for further information.

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4.4 Results

Comparison of the two methods on a core-by-core basis shows a general visual agreement of charcoal stratigraphy's and there is generally more charcoal recorded in the lower section of all three cores (Figure 4.4). Although it cannot be concluded with statistical certainty due to the large standard error as reported in Table 4-1 and despite the visual agreement of the charcoal stratigraphy's, the image analysis typically identified a larger number of small-sized particles, (size classes one to three) with the exception of core one size class three. The differences between the methods for the number of particles in the two largest class sizes were less pronounced (Table 4-1). Only core 3 yielded statistically significant differences between the methods for the number of small-sized particles. Interestingly, core 3 was collected closest to the peat basin border and had a larger charcoal record than the two other cores that were collected more towards the centre of the peatland. Even though the distances from core 3 to the other cores were only a couple of metres, core 3 contained significantly more charcoal particles than the other cores, and this was the case for particles in all size classes (Figure 4-3 and Table 4-1).

An important feature of the difference in the charcoal record among the cores is that the proportion of the largest particles increased significantly with decreasing distance to the peat basin margin (Figure 4-4 and Table 4-2), for example, the average proportion of particles in size class five increased from 6% in core one to 20% in core 3 as estimated by the mass quantification method. The corresponding increase as determined by the image analysis was from 2% to 5% (Figure 4-4).

A further difference between the two methods is that the image analysis rendered larger variations in the estimates of charcoal particle number as compared to the mass quantification. The magnitude of this variation differed among the particle size classes (Table 4-1), which in turn resulted in correlations that were particle size class specific when the two methods were compared as regard charcoal particle number estimation (Table 4-3). For example, the Spearman correlation coefficients ranged from 0.526 ($p = 0.007$; $n = 47$) to 0.616 ($p < 0.0001$; $n = 47$) among the particle size classes, with size class five having the highest value (Table 4-4).

Furthermore, there are other recording differences between the two methods as the mass quantification method found charcoal fragments in two samples at the depths of 80 and 90 cm in core one, where none were recorded using the image analysis method. In the same way, the image analysis identified charcoal particles that were not found by the mass quantification, that is, at a depth of 32 cm in core one (Figure 4-3).

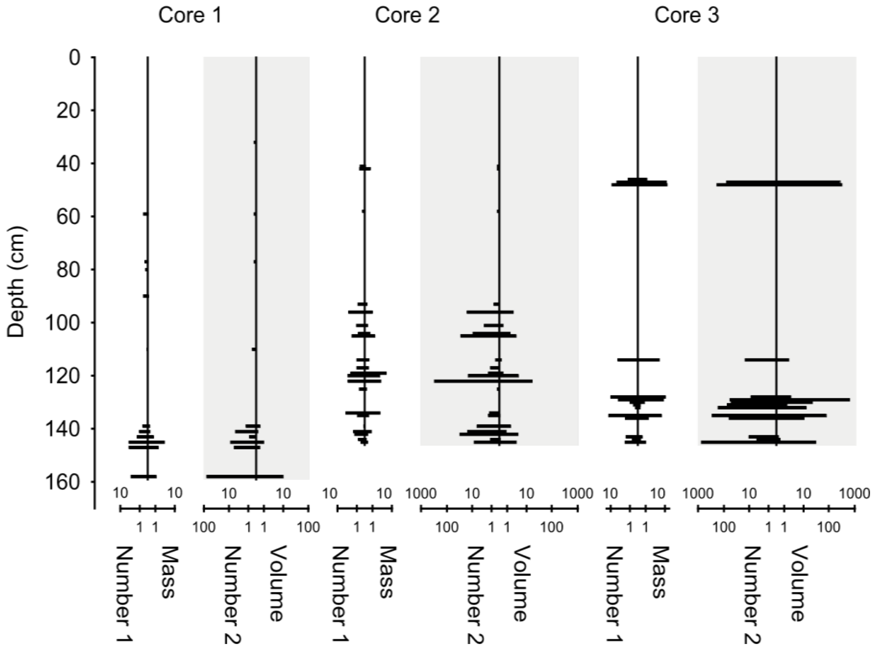


Figure 4-4 **Charcoal records in three neighbouring peat cores collected at different distances from the margin of a small peat basin. Horizontal bars show the number (count), mass (g) and volume of charcoal particles (cm^3) as estimated by two different methods, where number one and mass were estimated by a mass quantification method based on manual hand picking, and number two and volume (light grey shaded) were estimated by automated image analysis; see 'Material and methods' for further information. Core one was collected in the centre of the peat basin and core 3 was collected closest to the basin border. The distance between cores one and two was ca. 2 m, and the distance between cores 2 and 3 was ca. 3 m. Note logarithmic scale.**

	df	*F* (*p*)
Method (M)	1, 44	**13.93 (<0.001)**
Core (C)	2, 44	**5.31 (0.009)**
M × C	2, 44	0.18 (0.840)

Table 4-2: Split-plot ANOVA testing for the effect of method and core number on the proportion of charcoal particles (log-transformed) in size class 5.

Bold values indicate significant effects at p < 0.05.

Factor	χ2	*df*	Pr (>χ^2)
Method	0.3968	1	0.529
Size class	277.8227	4	<0.001
Core	26.0406	2	< 0.001
Method: Size class	46.6231	4	< 0.001
Method: Core	56.8389	2	< 0.001
Size class: Core	9.8920	8	0.273
Method: Size class: Core	6.6505	8	0.575

Table 4-3: GLMM ANOVA (Analysis of Deviance Table – Type II Wald chi-square tests) showing the likelihood that the single variables (method, size class, core number), two and three variable combinations have a significant effect on the proportion of charcoal particles.

GLMM: generalized linear mixed model.

4.4.1 *Image analysis as predictor of charcoal mass*

Average total charcoal particle volumes ranged from 5 to 105 mm^3. cm^{-3} among the cores, with the highest values for core 3 (Figure 4-5a). The volume of the two smallest size classes was almost negligible as the volume of the largest size class five made up 90% of the total volume. Average total charcoal area showed the same pattern as for volume and ranged from 3.1 to 41.0 mm^2. cm^{-3} (Figure 4-5b).

The image analysis variable that correlated the best and could thus explain most of the variation in charcoal mass as quantified by the mass quantification method, was the total charcoal particle volume ($r_s = 0.633$; $p < 0.0001$). However, total particle number correlated almost as well as total volume. We found slightly weaker correlations for particle number in size class 3 and 5, which were still strong and highly significant (Table 4-4). We also found generally significant correlations between the methods for the number of particles in each size class (data not shown).

4.5 Discussion

4.5.1 *Method discrepancies*

As the mass quantification method is based on manual hand picking, it was expected that the image analysis would identify a larger number of small particles, simply because these are hard to detect and sort out from the peat matrix by hand picking. This implies that the difference between our two methods will be most accentuated for charcoal records that are dominated by small particles. Image analysis, using the free programme ImageJ (imagej.nih.gov/ij), can be used to identify and count charcoal fragments that are down to a few microns in size, although >0.002 mm^2 (>44.7 µmm length) is a useful threshold to use to eliminate erroneous groups of pixels. Previous work has suggested that image analysis estimates of fragment number may be lower than those visually determined because particle edges have a lower optical density than the centre, resulting in small particles not being observed and larger particles appearing smaller (Hawthorne and Mitchell, 2016; Horn and Sanford, 1992; Macdonald *et al*, 1991). In this study, this effect has been reduced by increasing the threshold value. This is possible if several techniques are used such as elimination of non-charcoal material using a low magnification binocular microscope and then careful choice of the threshold value used in the ImageJ programme combined with non-inclusion of particles <0.002 mm^2 (<44.7 µmm length). The sample volume in this study, although large, is within the contemporary recommended volume size (Higuera et al, 2010). For peak detection (not explored in this study), the desirable volume size is that which results in average non-peak samples of >10 pieces and peak values of at least 20 pieces (see Higuera *et al*, 2010).

Image variable	Charcoal mass
Particle number in size class 1	**0.568**
Particle number in size class 2	**0.575**
Particle number in size class 3	**0.607**
Particle Number in size class 4	0.526
Particle Number in size class 5	**0.616**
Total particle number	**0.628**
Particle volume in size class 5	**0.590**
Total particle volume	**0.633**

Table 4-4: Spearman rank order correlation coefficients between nine charcoal variables as estimated by an image analysis method and charcoal mass as estimated by manual hand picking.

See 'Material and methods' for further information about variables and methods. Correlations significant at level $p < 0.0001$ are in bold ($n = 47$).

A small number of samples that contained many small charcoal particles among many dark minerogenic fragments needed to be subsampled. The image analysis is obviously limited by the capabilities of the camera, the resolution of the computer monitor and the time available to eliminate minerogenic material through careful processing. What does the presence of this minerogenic material imply from a palaeoecological perspective? How could changes in sediment flux, induced by fire or other disturbances affect the results obtained in this study, in particular, for the image analysis method? Environmental disturbances, such as storms and human activity, can increase the quantity of mineral matter transported into sediment. Eliminating the addition of a significant amount of non-charcoal dark, opaque material to the quantity of charcoal fragments in the analysis needs consideration. In this study, both methods employed processing elements that required evaluation of individual particles on a sample by sample basis. The mass quantification hand picks charcoal particles. The image analysis method initially uses sieving to eliminate most of the larger pieces of minerogenic material and then a light microscope and a pipette to further eliminate non-charcoal material. Although this increases the image analysis method processing time initially, it does provide more accurate results and reduces processing time at the image stage. Both methods can be used to obtain valuable insights of other organic material in the sediment. In contrast to the detailed results given by the image analysis, hand picking is likely to underestimate the importance of fire disturbance given that the charcoal record is dominated by a large number of small particles. In a palaeoecological perspective, it is thus clear to us that the image analysis is superior to hand picking as it has the potential to provide higher resolution and thereby more precise descriptions of fire importance and fire history. However, charcoal particle number is not necessarily a robust indicator of fire size or severity, for example there are differences between crown and surface fire (Leys *et al*, 2013).

Interestingly, the image analysis revealed charcoal particles at one depth in core one (i.e. 32 cm) while no charcoal was detected by the mass quantification method at the same depth (Figure 4-4). In contrast, the mass quantification method found charcoal that was not detected by the image analysis at two depths in core one (i.e. 80 and 90 cm). In these cases, there were always only very minor amounts of charcoal in the samples, and it is plausible that the lack of consistency can be explained by an uneven particle distribution between the two peat slice halves that were analysed at the different laboratories in Norway and England. Another possible explanation is that black plant remains, for example, rhizome epidermis of horsetail plants (*Equisetum* sp.), were erroneously identified as charcoal by the mass quantification method.

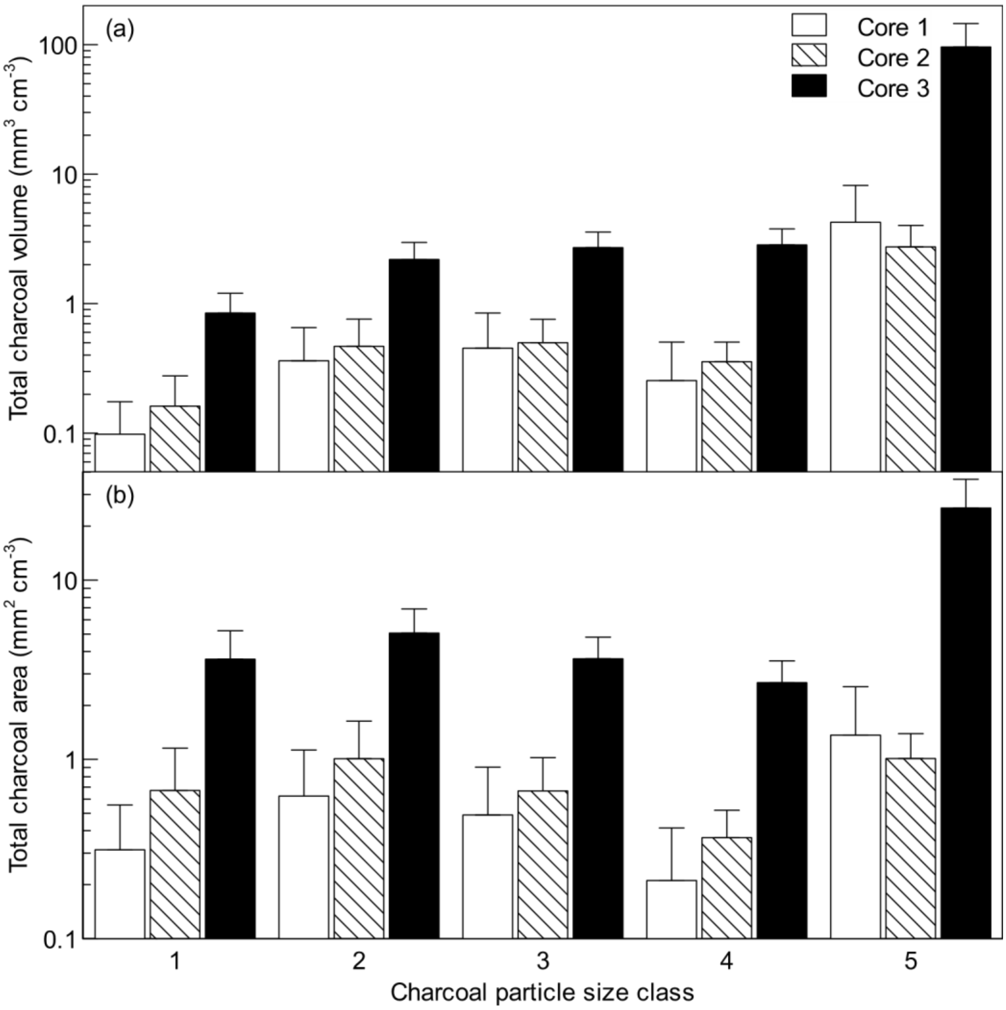


Figure 4-5: Total (a) volume and (b) area of charcoal particles in five size classes from three neighbouring peat cores as estimated by automated image analysis. Size class 1 (mm) = 0.20–0.49; 2 = 0.50–0.99; 3 = 1.00–1.49; 4 = 1.50–1.99; and 5 = >2.00. Note logarithmic scale on the vertical axes.

Our study further suggests that sample preparation methodology is an important determinant of fragment number and should be considered when making regional fire summaries comprising multiple sites and investigators. For example, as incompletely pyrolysed charcoal particles degrade faster than completely pyrolysed particles (Knicker, 2011; Rumpel and Kögel-Knabner, 2011), it is likely that the discrepancy between the results from our two methods will be largest for incompletely pyrolysed particles because these are less resistant against our use of bleaching in the sample preparation process, which is known to eliminate charred particles and only leave fully pyrolysed and carbonized material. Thus, the degree of similarity between different methods to quantify charcoal is not only dependent on intrinsic methodological differences but also on the charcoal properties itself. In this context, it is not only the degree of pyrolysis that matters but also charcoal stock origin is of importance – for example, resinous pine charcoal is more resistant against degradation than charcoal from more soft wooded spruce. That charcoal particle number estimates differ between methods is further corroborated by Ali et al. (2009). Taken together, this underpins the difficulties in selecting reliable and comparable methods for charcoal quantification.

On the contrary, our two methods are more comparable as regards estimates of charcoal pool size. The reason for this is that they did not differ significantly in the estimates of the largest and easily detectable particles (see Table 4-1), which by far make up the majority of the charcoal mass and volume.

4.5.2 *Correlations between image analysis and mass quantification*

Particle number, as estimated by the two methods, was in general strongly correlated, and this was the case for all particle size classes except for particles in size class four, which was the size class that comprised fewest particles (Table 4-1). Total particle number and total particle volume were those variables that correlated strongest with charcoal mass (Table 4-4). This was an anticipated result as Weng (2005), Ali *et al*. (2009), Leys *et al*. (2013) and Crawford and Belcher (2016) have shown that charcoal particle volume estimates are more accurate and robust to depict the amount of charcoal than particle number. However, due to the strongly skewed distribution of charcoal particle data in our study, it is not possible to precisely estimate the explanatory power of variables that were estimated by the image analysis. Total particle mass correlates significantly with total particle volume at $r_s = 0.633$ ($n = 47$) showing that the two methods are comparable for these variables although using volume can produce misleading interpretations of fire regimes due to the variation generated (Leys *et al*, 2013). Total particle mass correlated significantly with total particle number (image analysis method) at $r_s = 0.628$ which cannot be explained easily. Total particle number (mass method) correlates significantly with total particle number (image analysis method) at $r_s = 0.572$; however, this is not consistent across the size classes; classes one and five correlate significantly, but size classes two, three and four do not. There is still a need for more comparative studies of methods to find statistically significant variables that can be used to compile multiple site datasets.

4.5.3 *Methodological implications of differences among peat cores*

Variability in particle size and morphology of particles depends on the ratio between Potential Charcoal Source Area (PCSA) and fire size, and the absolute size and location of fire within the PCSA (Conedera et al, 2009). Discriminating PCSA using particle size distribution can be a useful tool in identifying regional and local fire events (Iglesias et al, 2015). Although all class sizes of particles are present in both regional and local fires, meso and macro charcoal (>180 µm) tends to represent more local fire events and micro charcoal (<180 µm) tends to represent regional fire events (Higuera et al, 2007, 2010). Here, local fires as represented by charcoal particles >250 µm (major axis length) were subdivided into five class sizes. This study has shown that methodological differences can create biases in class size quantifications and hence this can have implications on the interpretation of fire regimes if not all size classes are adequately represented. Fires further away and less intense could potentially be picked up by some methods and not others. Charcoal fragment deposition patterns are unique to each fire event; however, results herewith highlight differences in spatial deposition that would benefit from further study. The proportion of size classes between the cores is relatively similar given the large *SE* values; however, the amount of charcoal generally increases from core one to core three for both methods. This could imply that the amount of charcoal fragments found in sediments is a better indication of site proximity to palaeofire events than size class distribution.

The gradual increase in charcoal particle size when moving closer to the peat basin border (from core 1 to core 3) has important implications in palaeoecological and methodological perspectives. This is because large charcoal particles (>0.5 mm) are typically locally deposited (evidence from contemporary fires may mean this value needs to be adjusted to a higher threshold) and thus indicative of in situ local fires (Clark, 1988; Gavin, 2006; Ohlson and Tryterud, 2000). Given this, truly local fire histories will be more detectable and most clearly revealed in samples collected close to the peat basin border. In contrast, the probability in detecting local fires decreases in samples collected further away from the basin border because of the dominance of small charcoal particles which are known to disperse over long distances and could thus be indicative of non-local fires (Clark, *et al,* 1998). Previous studies by, for example, Pitkanen *et al*, (2001) and Ohlson et al. (2006) corroborate the occurrence of such peat-basin-specific patterns in the charcoal record as they also document decreasing amounts of charcoal from the border towards the centre of different types of peat basins in terms of both charcoal band layers and charcoal particle numbers. Thus, sound conclusions about charcoal record sizes and fire histories cannot be drawn from single peat cores, as every peat sample location will render unique and context-dependent results. Perhaps future similar studies will lead to the formulation of a weighting scale that can be applied to charcoal fragment quantities to allow for differences in charcoal quantity dependent on the distance of the core site relative to the peat basin edge. Differences in charcoal quantities between size classes for the different methods as shown here highlight the importance of selecting datasets using similar methods for isolation of charcoal fragments and for recording charcoal concentrations when comparing charcoal fragment records.

4.6 Conclusion

We draw five main conclusions from our study:

1. The mass quantification method and the image analysis method rendered markedly, and in some cases significantly, different results for small-sized particles (<1 mm in diameter), but not for larger particles.
2. The difference between the methods increased with increasing amounts of charcoal in the records.
3. Total charcoal particle volume, as estimated by the image analysis, was the best predictor of charcoal mass.
4. Size matters; the largest size class of the charcoal particles made up 90% of the total charcoal volume and mass.
5. The charcoal records differed significantly among closely neighbouring peat cores in one and the same peat basin.

Both the mass quantification method and the image analysis method have identified a similar range of samples where charcoal fragments, and hence incidence of local fires, occur. Across the three cores, there is an increase in charcoal towards the deeper parts, and the two cores that were collected closest to the peat basin margin (i.e. cores two and three) show earlier peaks in charcoal and did also contain significantly more charcoal than the core that was collected in the centre of the peatland (i.e. core one). There are differences between the methods; charcoal volume data (image analysis method) compared with mass data (mass method) for the different size classes showed greater statistical significance than comparing size classes irrespective of method. Our study has also shown that different particle size classes do not necessarily compare across methods. A further result is that multiple cores collected close to each other in one peatland differ significantly in their charcoal records. No charcoal quantification methods render the same results, and although there is still a need for a common and unifying method to enable reliable comparisons of results from future studies, quantification of charcoal fragments using a size measurement rather than a count provides more significant results in cross-site or multiple-core studies.

Chapter 5 Exploring Holocene fire regimes, vegetation dynamics, climate and human impacts for Robinsons Moss, Peak District

5.1 Abstract

This study investigated the impact and long-term role of fire within an upland ombrotrophic peat bog in the Peak District, U.K. The results show that the fire regime was driven by a complex relationship with climatic conditions, biofeedback mechanisms and the vegetation. The impact of a significant, early fire around 7300 years BP is shown in the soil chemistry and fungal spore assemblage. A shift from Poaceae to Ericaceae occurs post this fire event. Several other significant fire periods are concurrent with U.K. wide expansions in human activity, however, the overall percentage that fire explains the vegetation dynamics does not exceed 18%. This low value reflects the low impact that fire has on this ecosystem. Correlation between fire events with *Calluna vulgaris* and *Quercus* indicates that these are probably the taxa that were burning at different time periods and at different spatial scales at Robinsons Moss. *Calluna* is regionally dominant from the start of the record and tree taxa expand and decrease as climatic conditions ameliorate and deteriorate. Periods of intense fire events probably accelerated the process of peat development impacting on both the local and regional vegetation dynamics. Although there is evidence for herbivore grazing and human activity, climate is thought to be the main ecosystem driver until ~ 2000 years BP with the vegetation dynamics responding to wet/dry shifts. Local vegetation at Robinsons Moss included deciduous trees until around 800 years BP.

5.2 Introduction

We are uniquely fire creatures on a uniquely fire planet (S.J. Pyne)

There is a paucity of long-term records for The Peak District, despite being an area known for its long fire history and that the upland areas are sensitive to changes in climatic conditions. Hence the fire record constructed for this study is important in revealing information about the local conditions driving the fire-vegetation-climate relationship in upland ombrotrophic bogs for Northern Britain during the Holocene. This study is also important in that it analyses differences in sizes of charcoal fragments in relation to reconstructed fire histories (Hawthorne et al, 2018).

Peat sediments are excellent archives of Holocene fire history. Robinsons Moss is an ombrotrophic mire, sensitive to hydrological and therefore climatic changes so provides ideal sediments to study the relationship between fire, vegetation dynamics and climatic conditions. Although mires are stable environments, disturbances can cause the environmental conditions to change and the stability threshold may be crossed (Bragg *et al*, 2001). Tallis (1991) suggests that waterlogging conditions caused the initial peat formation 9000 years BP at Robinsons Moss causing gley soils to become podsolized. Peat formation occurred this early at relatively few sites in the U.K. Examples of early Holocene peat deposits can be found in Wales (Moore *et al*, 1972; Chambers *et al*, 1982). Waterlogging of soils can be due to a complex mixture of factors of such as deforestation, fire or increase in precipitation. At Robinsons Moss, the cause of peat initiation has been discussed by Tallis (1991) and concluded to be due to natural processes. Tallis (1991) provides the only detailed description of the Holocene fire history of the Peak District. His evidence suggests that Mesolithic tribes had a major impact on the South Pennine region. Turner *et al* (1993) suggests that changes in pollen assemblages tend to be more climatically based except at the 450- 680 m a.s.l. altitude where human activity is more likely to have caused changes in the pollen (Robinsons Moss is at ~ 500 m a.s.l.). Tallis suggests that these Mesolithic tribes were operating at the treeline which tended to fluctuate dependent upon the climatic conditions. For example, Tallis notes that the treeline was in recession from 5300 years BP during a European wide cooling period and that *Pinus* and *Betula* increased during a warm and dry period from 4300 – 4000 years BP (Tallis, 1983). Although Tallis concludes that peaks in charcoal fragments relate to tree taxa abundance, he also states that it is unclear as to the degree that climatic changes and fire events contribute to the vegetation succession at Robinsons Moss and the surrounding slopes. Hughes *et al* (2000) suggests that Mesolithic tribes in the Peak District were burning *Calluna* on the dry hummocks of the blanket bog, which developed post a base-rich to bog transition.

For the Peak District region, evidence suggests that it is changes in climatic conditions rather than human activity that is the cause of increases in fire events pre 5000 years BP (Turner *et al*, 1993; Hughes *et al*, 2000; Tipping *et al*, 2008). There is greater evidence for human activity post 5000 years BP (Mackay *et al*, 1994; Mighall *et al*, 2004) than pre 5000 years BP. This agrees with the conclusions in Molinari *et al* (2013) with the primary role of vegetation, precipitation and temperature related parameters in explaining fire dynamics for early Holocene. For middle and late Holocene, Molinari concludes that anthropogenic land-cover change is more influential than vegetation and temperature-related parameters.

U.K. wide evidence for repeated disturbance and regeneration phases can be found in several studies (Innes *et al*, 2010; Froyd, 2008; Fyfe *et al*, 2003;) but the significance of human activity in woodland disturbance remains unclear (Ryan & Blackford, 2010).

5.3 Aims

This study aims to explore fire-vegetation-climate relationships using peat deposits from Robinsons Moss, Peak District, an upland ombrotrophic peat bog using a multiproxy dataset of high -resolution charcoal fragments (macroscopic and microscopic), pollen grains, spores and a range of Non Pollen Palynomorphs (NPPs) which includes coprophilous fungi. The evidence for shifts at different temporal periods between stable and semi stable states such as the base-rich to bog transition will be explored using NPPs to identify local conditions in conjunction with palynology used to explore major shifts in the dominant vegetation.

The research question that will be addressed is:

A. How (and why) has the fire regime altered during the Holocene at Robinsons Moss?

5.4 Site and study area

Robinsons Moss

Images of Robinsons Moss and a location map are shown below.

Figure 5-1: Robinsons Moss (images by K. Halsall, 2009).

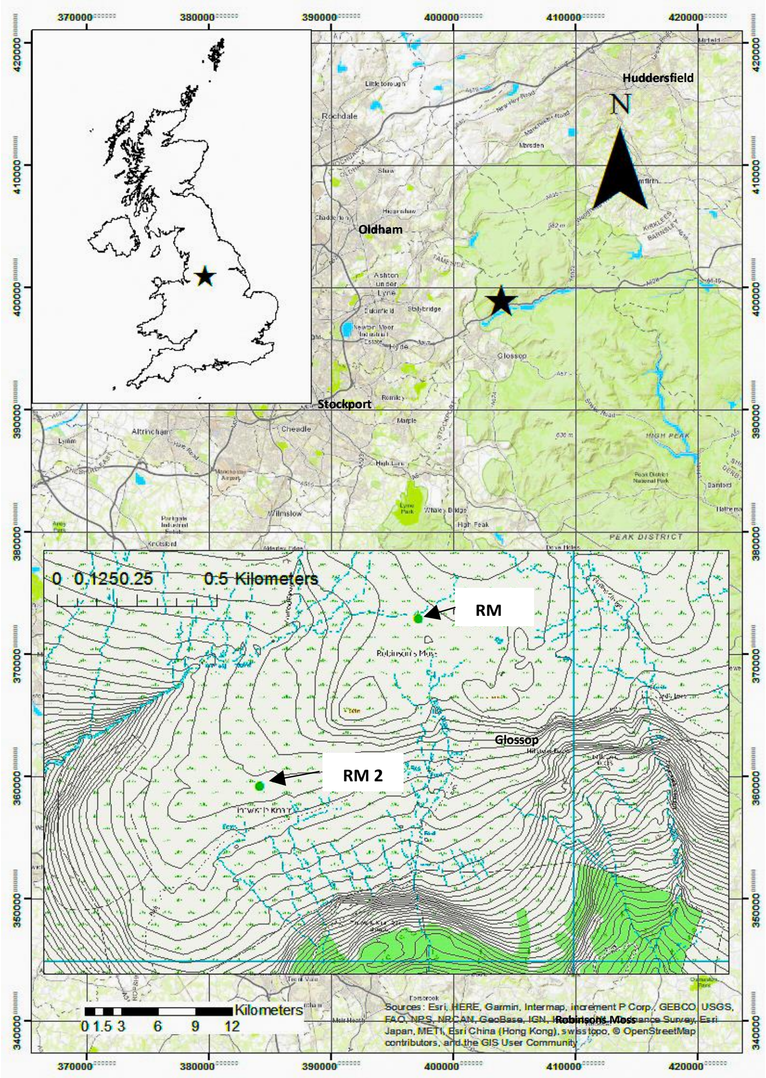


Figure 5-2: Location map for Robinsons Moss.

Robinsons Moss (53° 49' 6.12" N, 1° 93' 6.63" W), elevation 500 m. a.s.l., is a relatively undisturbed ombrotrophic peat bog in the Peak District National Park (figure 5-1). In common with most of the Peak District, it is privately owned. Robinsons Moss is owned by United Utilities but does have public access. It is managed to maintain current biodiversity and condition under several National and International Directives such as Convention on Biological Diversity, European Union species and habitats directive; Kyoto and the Water Framework Directive. This area was previously grazed by sheep in the early 1990's at a density of 0.66 ewes per hectare. After 1992 the grazing was reduced. Prescribed burning has not taken place at Robinsons Moss since 2004 and grouse shooting stopped in 2010 with the establishment of a partnership between United Utilities and the Royal Society for the Protection of Birds (information from Ed Lawrence, Wildlife Warden, East Area Catchment Team, United Utilities, 2015).

Robinsons Moss has previously been described by Tallis & Switsur (1990) as a shallow saucer-shaped basin 0.5 Km in diameter at 485 – 510 m a.s.l. on the high ground immediately to the North of Longdale and drained by the headwaters of Arnfield Brook, Rawkin's Brook and Hollins Clough. Tallis sampled the bottom 1.7 m of a 4.1 m peat core at National Grid reference SE 045001 at an altitude of 500 m a.s.l. The core site in this study was taken close to the original core site used by John Tallis in his published study (1991).

The current vegetation species in the hummock hollow system on Robinsons Moss include *Deschamsia flexuosa, Nardus stricta* on tussocks, Sphagnum mosses, *Eriophorum angustifolium*, Cyperaceae and *Molinia caerulea*. *Calluna vulgaris* and several grass taxa are found at the edge of the bog and on the surrounding area. As the slope descends to the three reservoirs at the base of the slope, *Betula*, conifers, *Sorbus* and other trees are present. Higher slopes to the North and West are a mosaic of peat bogs and heaths dominated by *Calluna vulgaris*. Robinsons Moss basin and higher areas are watersheds that drain into Reservoirs. This water is then used to supply the local conurbation of Manchester. Robinsons Moss has a high water table. Between 1981 – 2010, the mean annual January temperature was 2.85 ^{o}C and the mean July temperature was 14.95 ^{o}C. For days where the rainfall was > 1mm per day, the mean annual July rainfall was 87.8 mm yr^{-1} and mean annual January rainfall was 136.5 mm yr^{-1}. The overall mean annual rainfall between 1981 and 2010 was 112.15 mm.yr^{-1}. For 2017, the annual rainfall was 276.73 mm.

5.5 Methods

Field, laboratory and Statistical methods

5.5.1 *Field method*

A 5 m long sediment core was extracted from Robinsons Moss in five sections in June 2009 using a 1 m long, 10 cm diameter Russian corer (Jowsey *et al*, 1966). Some of the sections are shown in figure 5-3. Sediment was extracted 1m at a time using a two hole system at overlapping depths. The extraction site is shown in figure 5-2. The sediment cores were removed from the corer, transferred to gutter sections and wrapped in cling film at the point of extraction. They were stored below 5 °C at the University of Liverpool. Prior to sectioning, the core surface was cleaned to avoid contamination and then cut into 479 samples at 1 cm intervals.

Figure 5-3: Various sections of the cores extracted from Robinsons Moss, 2009 showing charcoal bands and different stages in vegetation succession.

5.5.2 *Pollen analysis*

Sediment < 300 µm remaining in samples after preparation for testate amoebae analysis (see 5.5.8) were prepared for pollen analysis as described by Chambers *et al* (2011) and Moore & Webb (1992). Sub samples every eight, then, four then two cm depending on the section under investigation were prepared. Samples were treated with hydrochloric acid (HCL) and sodium hydroxide (NaOH) before being sieved at 195 µm. The finer sample residues were treated with sodium pyrophosphate to disaggregate the sediment prior to acetolysis to remove soluble cellulose. Samples were stained with safranin and mounted in glycerol on microscope slides prior to counting. A Nikon light stereomicroscope at magnification x400 was used for counting pollen grains, spores, microcharcoal and NPPs. A total of 300 terrestrial pollen grains were counted per sample where possible. Some samples contained a low pollen count, but at least 100 terrestrial pollen grains were counted in these samples. Pollen grains were identified using Moore & Webb (1992) and Beug (2004) to species level where possible. The data were compiled using TILIA and TILIA

GRAPH version 2.0.41 (Grimm, 2011). Zones were created using the CONISS (stratigraphically constrained cluster analysis) programme within TILIA using selected terrestrial pollen taxa above 1% (Grimm, 1987).

5.5.3 Charcoal fragments

Microcharcoal analysis

Charcoal particles were counted on pollen slides in two fractions; >10 – 50 µm and > 50 µm however only particles > 50 µm were used in the analysis as this fraction represents a more accurate representation of microcharcoal abundance. Concentration of microcharcoal fragments was calculated by dividing count by volume of sediment (number of particles / cm^3).

Macrocharcoal analysis

A known volume of sediment, either 3 cm^3 or 1.5 cm^3 was disaggregated using sodium polymetaphosphate (Calgon) and left in a petri dish overnight. After gently washing through a 250 µm brass sieve, 5ml of 6% sodium hypochlorite (active ingredient is 8% Chlorine in undiluted solution) was added in deionised water. The petri dishes were again left overnight and then the samples were rinsed gently using a 125 µm brass sieve to retain any fragments broken by the processing. To achieve a consistent bleaching effect, extra bleach was added to some highly humified samples. The samples were photographed on a light table with a Canon ixus (HS camera with 12x optical zoom) camera. The images were initially analysed using Scion Image (https://scion-image.software.informer.com/4.0/), however as this became an unsupported programme, ImageJ (imagej.nih.gov/ij/download.html) was then used. The charcoal fragments were identified with a threshold greyscale value of 56 (no units). This threshold value was determined by identifying the mean value (repeated for several charcoal fragments), where a stable number of pixels occurred. A small number of samples with very small pieces of charcoal were analysed at a higher threshold of value of 157 (these charcoal fragments were generally less than 0.005 mm^2 so they were of minor significance to the overall area value). Total area of charcoal fragments was presented as influx (mm^2/cm^2/yr). A lower limit of 0.002 mm^2 was set so that non charcoal dark pixels were not included in the image analysis and the area quantification (Halsall, 2018).

5.5.4 *Radiocarbon dating*

Small peat samples (5 g) from four different depths were selected for AMS Radiocarbon dating (tables 5.1 and 5.2). The radiocarbon dates were measured at the Radiocarbon dating laboratory, Lund University, Sweden, 2013. Plant stems were removed from the samples as they can give a younger age than the actual peat. The dates were calibrated using IntCal13 as part of the Clam package in R (Blaauw, 2010) The calibrated dates were confirmed by using the Bacon programme in R (Blaauw & Christen, 2011).

5.5.5 *Non Pollen Palynomorphs (NPP) analysis*

Sediment samples prepared for pollen analysis (see 5-5-2) were mounted on microscope slides using glycerol. A selection of NPPs were identified and counted on these slides using a guide prepared by Van Geel and Aptroop (2006). Fungal spores were counted in two separate ways. Initially NPPs were counted at the same time as pollen grains until at least 300 terrestrial pollen grains had been counted. Extra fungal spores were counted (including coprophilous fungi) until at least 100 Lycopodium exotic spores were counted. Counts of NPPs were then expressed as concentration (no. / cm^3) using the respective exotic Lycopodium counts and displayed on Tilia Graph (Grimm, 2011).

5.5.6 Near Infrared Reflectance Spectroscopy NIRS analysis

NIRS is a rapid method used to determine peat characteristics. As it is less time consuming than conventional methods, contiguous samples at high resolution can be analysed. The method is non-destructive and requires very small volumes. Peat samples from Robinsons Moss were calibrated with peat samples of known organic and inorganic content for the presence of *Sphagnum* and *Calluna vulgaris*, bulk density and humification levels so that changes in organic and inorganic content could be calculated (McTiernan, 1998).

NIR spectra were measured and processed as detailed by Russell *et al* (2019). Measurement was by diffuse reflectance using an integrating sphere on a Bruker MPA Fourier-Transform NIRS system. All samples measured were freeze-dried, homogenised by grinding in a mortar, and lightly hand pressed, with the NIR spectra-based on combining 64 scans collected at 8 cm^{-1} intervals across the range 3595-12500 cm^{-1}. Spectra were transformed to first derivatives using a centrally-weighted Savitzky-Golay smoothing (SGA) algorithm. A novel procedure was used to quantify the concentrations of various organic components (Russell *et al,* 2019) using multiple regression of samples onto library spectra of selected end member materials.

5.5.7 X-Ray Fluorescence (XRF) analysis

Non destructive geochemical analysis of the oldest sample (479 – 350 cm depth) was carried out using X-ray fluorescence (XRF). Element concentrations were measured using an Energy Dispersive X-ray Fluorescence Analyser (ED-XRF). Freeze-dried samples were hand-pressed in 20 mm pots and measured under a He atmosphere using a Spectro XEPOS 3 ED-XRF that emits a combined binary Pd and Co excitation radiation and uses a high resolution, low spectral interference silicon drift detector. The XRF analyser undergoes a daily standardization procedure and has accuracy verified using 18 certified reference materials. (Boyle et al. 2015).

5.5.8 *Testate amoebae analysis*

Samples of a known volume were prepared for testate amoebae analysis using the standard method described by Booth *et al* (2010) prior to preparation for pollen analysis. This procedure was applied as the intention was to identify and analyse testate amoebae, however the samples did not produce sufficient abundance of testate amoebae to be of analytical use. Sub samples every eight, then, four then two cm depending on the section under investigation were prepared. 50 ml of distilled water was added to a known volume of sediment then two *Lycopodium* tablets were added as an exotic marker (Stockmarr, 1971), and the samples were simmered in a hot bath until the tablets dissolved. The sediment was washed through a 300 µm sieve. The filtrate < 300 µm was centrifuged at 300 rpm for 5 minutes and then decanted. 10 ml distilled water was added to the sample and then 1ml was extracted and transferred to a vial for testate amoebae analysis. The remaining sample < 300 µm was used for pollen analysis.

5.5.9 Statistical analysis

Statistical analysis of the macrocharcoal data was carried out using several statistical packages within the R statistical programme. The CHAR programme (Higuera, 2007) was used to separate the 'background' and 'peak' charcoal values with peak magnitude values determined using locally defined values (CONISS hierarchical cluster analysis). The programme also calculates the fire return intervals (FRIs: number of years between two consecutive fire events) and fire frequency over time smoothed using a locally weighted regression with a 500 year window (Figure 5-25). The CharAnalysis programme is available online at http:/phiguera.github.io/CharAnalysis). The raw charcoal data (particles/cm^2/yr) were interpolated to 18 year time periods. This is similar to the median temporal resolution for the entire record (17.1 years). The data was then decomposed into background and peak components with a locally weighted Lowess smoothing function robust to outliers, using a 500 year window. BCHAR was then subtracted to obtain the residual data defined as peaks in charcoal fragments. A Gaussian mixture model was then used to define a threshold value, t, set at the 95th percentile of the peak data to remove *noise* (natural and analytical effects) in the data by applying it to overlapping 1000 year intervals. Charcoal peaks shown as red crosses, are assumed to reflect the occurrence of local fire events occurring within ca. 1 km from the site (Higuera, 2007).

The charcoal peaks derived from macrocharcoal area values (Area/cm^2/yr) were subsequently screened with respect to the count sums using ARCO (Finsinger, 2014). This is a bootstrap method that resamples charcoal particle areas using the surrounding count values. Peaks with total areas significantly greater than expected by chance are deemed robust indicators of past fire events (Finsinger, 2014).

Ordination analysis

Ordination techniques are generally based on gradient analysis and data reduction and use eigenvalues or relationships between samples such as correlation to summarise ecological data. They can be used to arrange species along the major gradients to determine clusters of taxa that are responding to the same environmental factor. Several of these techniques can be completed using the VEGAN package in R (Oksanen *et al*, 2018).

Cluster analysis

Stratigraphically constrained sum of squares cluster analysis can be used to identify species that occur together or groups of samples with a similar fossil assemblage (Kovach, 1995) whilst retaining the stratigraphy, for example CONISS (Grimm, 1987).

Detrended Correspondence Analysis (DCA)

Correspondence analysis summaries the variation within a multidimensional dataset by describing the main trends as two eigenvectors, species scores and sample scores. Detrended correspondence analysis (Hill and Gauch, 1980) corrects for the unimodal "arch" created by the response curves and also corrects for the compression that occurs at both ends of the gradient on the second axis. Axis one identifies the most significant change that occurs within the data.

Principal Component Analysis (PCA)

Principle Component Analysis minimises the distance between correlated samples projected as multidimensional data by transforming the trend onto eigenvectors in order of decreasing variance. The second and subsequent eigenvectors are uncorrelated with previous eigenvectors. This is similar to multiple linear regression.

Redundancy Analysis

This is a linear technique that assesses the linear relationship between response variables (e.g. pollen percentages) explained by one or more environmental variables (e.g. charcoal flux). A constrained axis (RDA1) is calculated by applying a species score vector onto the charcoal data. This can then be used with the unconstrained PCA axes to explore the extent to which vegetation changes can be explained by the fire (charcoal fragment data). The total variance explained by fire is calculated by knowing the value of total "inertia" in the model. DCA can be used (and PCA) when the gradient on the first axis has a value between 1.5 and 3.

Correlation

Correlation coefficients between macroscopic and microscopic charcoal fragments with selected pollen taxa were calculated using Kendal's tau for non-parametric data. Other correlation techniques used include cross-correlation and the Corrgram statistical package in package R (Wright, 2018). The level of significance between individual species and charcoal fragments were also reported using 95% confidence limits.

Quantitative vegetation reconstruction

Regional and local pollen proportion estimates were calculated for Robinsons Moss using LOVE and REVEALS Landscape Reconstruction Algorithm (Sugita, 2007a, 2007 b). The LRA is a two-step model-based correlation algorithm than can be applied to pollen count data to estimate vegetation abundance (Fyfe *et al*, 2018). The first step involves applying the REVEALS model (Sugita, 2007a) to estimate regional vegetation composition using pollen percentages from several small sites in combination with species-specific pollen productivity and dispersal values. The LOVE model (Sugita, 2007b) uses the regional pollen proportion estimates derived from the REVEALS model with pollen productivity and dispersal values to estimate the distance weighted proportion of a selection of pollen taxa within the source area of the target site (Sugita, 2007b). Pollen productivity estimates and pollen fall speeds were obtained from Broström, *et al* (2008).

LOVE pollen proportion estimates were calculated using LOVE V4.6.1 (Sugita, 2007a). This allows for a more realistic regional review as local conditions vary across regions (Fyfe *et al*, 2018). The pollen source area was set to 400 m and increased at 10 m increments. The default wind speed of 3 m.s^{-1} was used. The estimated local pollen source distances were calculated at 10m increments until the estimates of all pollen source areas were $\geq$ 0 within 1 S.E. of the estimates for the regional pollen source distance. The pollen records used for the REVEALS and LOVE models are from sites above 240 m a.s.l.

5.6 Results and interpretation

5.6.1 Age depth models

Two methods have been employed to determine the calibrated ages for Robinsons Moss to check for agreement between the models. First CLAM (Blauuw, 2010) was used and the secondly the same radiocarbon dates were also entered into the Bacon Bayesian age-depth model in R (Blaauw and Christen, 2008). The results from the Bacon run are shown in figure 5-5 and table 5-1. All dates are shown in calibrated years BP. Atmospheric Pb pollution was used to determine a modern age for the Robinsons Moss core. High levels of Pb pollution can be detected in peat deposits from ombrotrophic bogs in the Peak District due to industrial activity in this region. Peaks can be detected dated to the British-Romano period, the medieval period, Victorian industrialisation and also recent increase in Pb pollution from cars during the 1970's (Rothwell, 2007). XRF analysis can be used to determine chronological changes in atmospheric Pb (ppm) deposited on the peat surface. For this analysis, two cores were compared, the main core used in this study taken from the centre of Robinsons Moss (4.79 m) and a second core taken in 2014 from the edge of Robinsons Moss (1.84m). Lead quantities within peat sediments are highly variable, and several cores would be needed to obtain early dates, however this study has made a tentative assumption that a date of 1975 can be assigned to a depth of 3cm as the two cores both show a peak at this depth.

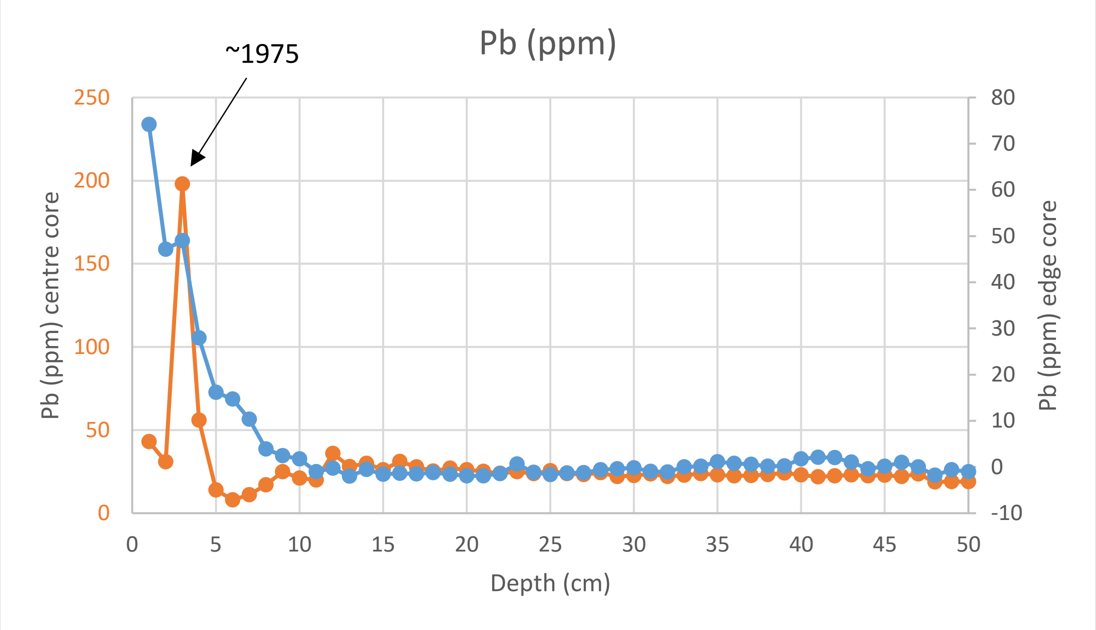


Figure 5-4: Comparison of Pb (ppm) between two cores taken from Robinsons Moss; Centre of bog (orange line), edge of bog (blue line).

Both cores show a peak at 3 cm (figure 5-4). Lead abundance is at a higher level at the edge of the core than the centre of the core prior to this peak.

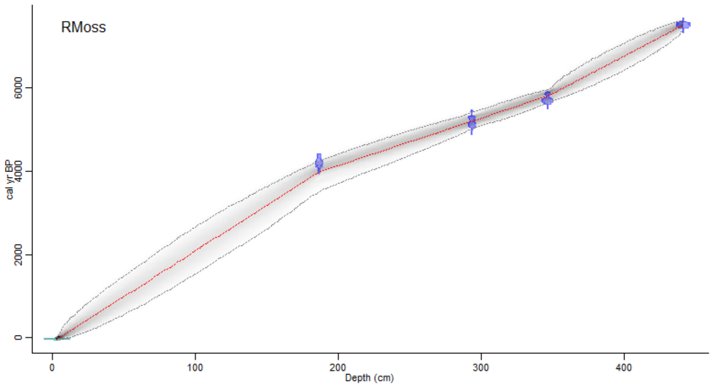


Figure 5-5: Bayesian Age-Depth model from four dated deposits using Bacon package in R (Blaauw and Christen, 2011) used to reconstruct Bayesian accumulation histories through combining radiocarbon and Peak in Pb level. Grey areas show 0.05 and 0.95 confidence limits.

Depth (cm) below surface	^{14}C yrs age yrs BP	Calibrated range yrs BP (2σ)	mean age 95% probability
3 -4	-25 ± 1	-53 - 6	-25
186 - 187	3807.5 ± 50	3493 - 4217	3958
293 - 294	4537.5 ± 50	5004 - 5398	5189
346 - 347	4970 ± 50	5636 - 5943	5798
441 - 442	6607.5 ± 50	7366 - 7617	7495

Table 5-1: Atmospheric Pb peak (modern date at 3-4 cm) and Radiocarbon dates from the AMS bulk sediment dating procedure for Robinsons Moss, Peak District with calibrated ages BP calculated using Bacon package in R (Blaauw & Christen, 2011).

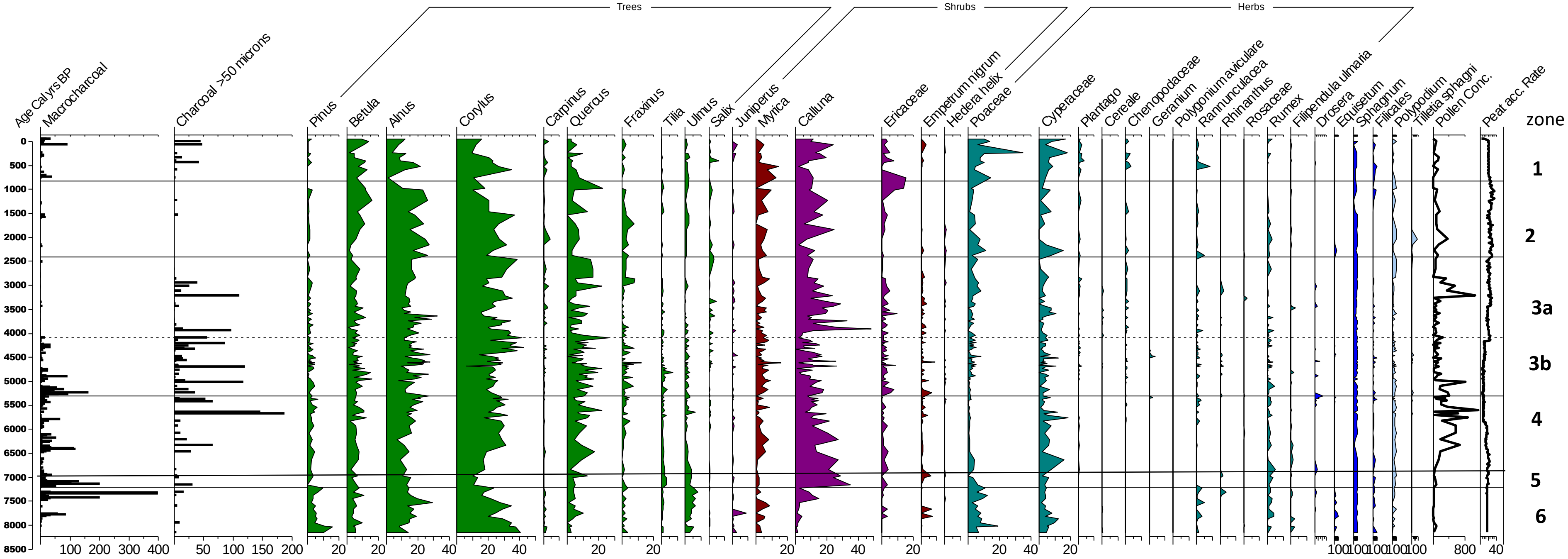


Figure 5-6: Macrocharcoal and pollen diagram showing macrocharcoal flux (area mm^2/cm^2/year), microcharcoal conc. (count/cm^3) and a selection of pollen (percentages) and spore conc. (count/cm^3).

The six zones reflecting major changes in the vegetation assemblages were defined using CONISS (Grimm, 1987) using a selection of pollen taxa over the entire 8200 years of the record for Robinsons Moss. The sub zones 3a and 3b are defined by a change in the macrocharcoal influx that is also reflected in the vegetation dynamics

5.6.2 *Pollen and charcoal results*

There are several major changes in the vegetation dynamics that occur over the 8200 years as shown in figure 5-6. *Calluna* shows major establishment at ~ 7200 years BP concurrent with a major reduction in *Corylus*, *Pinus* and Poaceae pollen percentage at the transition between zone six and five. Zones six, four and three b are periods of high local fire.

During zones three a and two (4900 - 800 years BP), macrocharcoal values are at a minimum, however microcharcoal values continue at a relatively high level throughout zone three a (4900 – 2850 years BP) but also reduce during zone two (2850 – 800 years BP). During zone one (800 years BP to present) both macrocharcoal and microcharcoal increase in quantity. Zone one shows a resurgence of trees preferring open wet conditions such as *Alnus*, *Betula* and *Corylus* and a reduction in *Quercus*.

Tree taxa are regionally present throughout the record although they generally reduce over the last 800 years. The macrocharcoal record indicative of more localised fire events indicates a period of relatively higher fire frequency and amplitude from 8200 to 4000 years BP. The microcharcoal record indicative of more regional fire events are highest during zone four, three a and three b i.e. fire events occur regionally during a later time zone than local fires indicating fire events shift further away from Robinsons Moss. Herbs are generally more diverse from 4900 to 3000 years BP including taxa indicative of disturbance such as *Plantago* and Chenopodiaceae.

5.6.3 Geochemistry results

The oldest samples (479 – 350 cm depth) were analysed for presence and abundance of elements. The results are shown in figure 5-28 and figure 5-7.

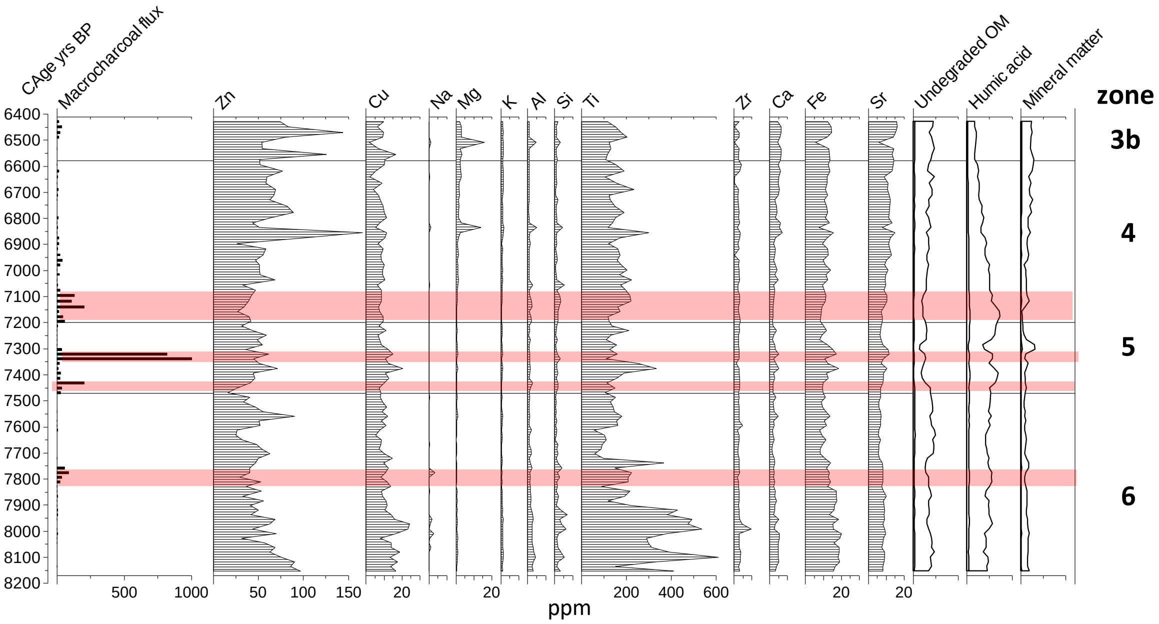


Figure 5-7: Charcoal, geochemical and NIRS diagram (Grimm, 2011) showing a selection of elements (ppm) calculated from XRF analysis and NIRS analysis (undegraded organic matter, humic acid and mineral matter) for zones six to three.

An inwash of clastic minerals (Na, K, Mg, Al and Ca) is associated with soil erosion events (Boyle *et al*, 2001; Mackereth *et al*, 1966; Bennett *et al*, 1992). Small increases in some of these elements can be seen in Figure 5-7. This could indicate that these erosion events occurred at a distance from the core extraction site at Robinsons Moss (Mackereth *et al*, 1966; Bennett *et al*, 1992). The fire events highlighted in figure 5-7 above (red bars), are associated with increases in humic acid, i.e. an increase in degraded organic material and a decrease in undegraded organic material indicating a reduction in the water table. These zones occur during periods of high fire events. As they are concurrent rather than lagged, this would indicate that drier climatic conditions provided conditions suitable for fire to occur. Immediately after fire occurs for example during high macrocharcoal quantities, 7475 – 7400 years BP, there is an increase in Ti. There is an increase in mineral matter after the major fire event 7350 – 7300. Both associations indicate erosion events in the surrounding area. Notable also is the increase in Fe post fire events. This could indicate a leaching of Fe and an increase in acidic conditions. There is a general increase in the peat material from 7050 years BP shown by the increase in undegraded organic material and mineral matter with a reduction in humic acid. This is concurrent with a reduction in the number of fire events. This is also indicative of an increase in the water table level driven by the influence of climatic conditions, in particular an increase in precipitation, in combination with waterlogging on the edge of the bog, which would reduce the likelihood of fire occurring.

5.6.4 Interpretation

The two diagrams, above, figures 5-6 and 5-7 show the association of fire events with changes in both erosional material and the vegetation dynamics. However, due to the complexities inherent within the positive, negative and lag effects between plant taxa and changes in temperature and precipitation, it is not easy to make direct links between fire events and changes in the vegetation dynamics and climatic conditions using data from only one site. Further study at a regional level could provide evidence of the dominance of climatic conditions or otherwise on the expansion of peat and changes in vegetation assemblages. This will be explored in chapter six. The six major vegetation zones are described below in terms of the fire frequency and fire return interval and the vegetation dynamics.

Zone 6: Mixed tree and open landscape in base-rich conditions (8153 – 7470 years BP)

Vegetation reconstruction of the earliest zone in this study suggests base-rich conditions with Poaceae*, Equisetum*, Filicales, *Filipendula*, *Rumex*, *Ranunculus* and other species suggesting openness and dampness with plants such as *Viola palustris.* Base-rich conditions are also seen in the NIRS data in figure 5-7 with higher levels of humic acid than in later millennia. Tree taxa such as *Corylus, Alnus* and *Betula* were probably present on the shallow peat bog, growing on the hummocks. Figures 5.9 also shows the presence of fungi associated with rotting wood e.g. *Triptenospora elegans. Corylus* and Poaceae decrease post these major local fire events, whilst *Calluna vulgaris* shows a resurging trend. Tallis (1983) found *Betula* tree remains at the base of a 3.35 m core radiocarbon dated to 7550 ± 60 and *Salix* remains 47 cm higher. *Betula* remains were also found at Featherbed Moss, near to Robinsons Moss dating to 7550 ± 60 (Tallis, 1983). In his later work Tallis (1990) suggested that an amelioration of climatic conditions occurred during the expansion of the trees followed by an increase in precipitation, waterlogging and expansion of the peat which covered the trees growing at the treeline. He also describes the sensitivity of Robinsons Moss to even slight changes in climatic conditions that is reflected in hydrological changes in the peat basin i.e. wetter, waterlogged soils 7800 to 7000 years BP, and subsequent effects on changes to the treeline and expansion of peat. However, there is further complications in the environmental conditions for Robinsons Moss at this time driven by the impact of other disturbances such as human activity for example the burning of trees by Mesolithic tribes. Figure 5-8 below shows the presence of dung using the proxy of coprophilous fungi, *Sordaria* and *Podospora* taxa in zone six. Tallis (1990) describes the probable increase in grazing by herbivores such as Red Deer, shown by an increase in Poaceae taxa from 8200 – 6800 years BP. An increase in grazing can be associated with opening up of natural areas by Mesolithic tribes but could also be a natural expansion of herbivores in more open post-fire areas.

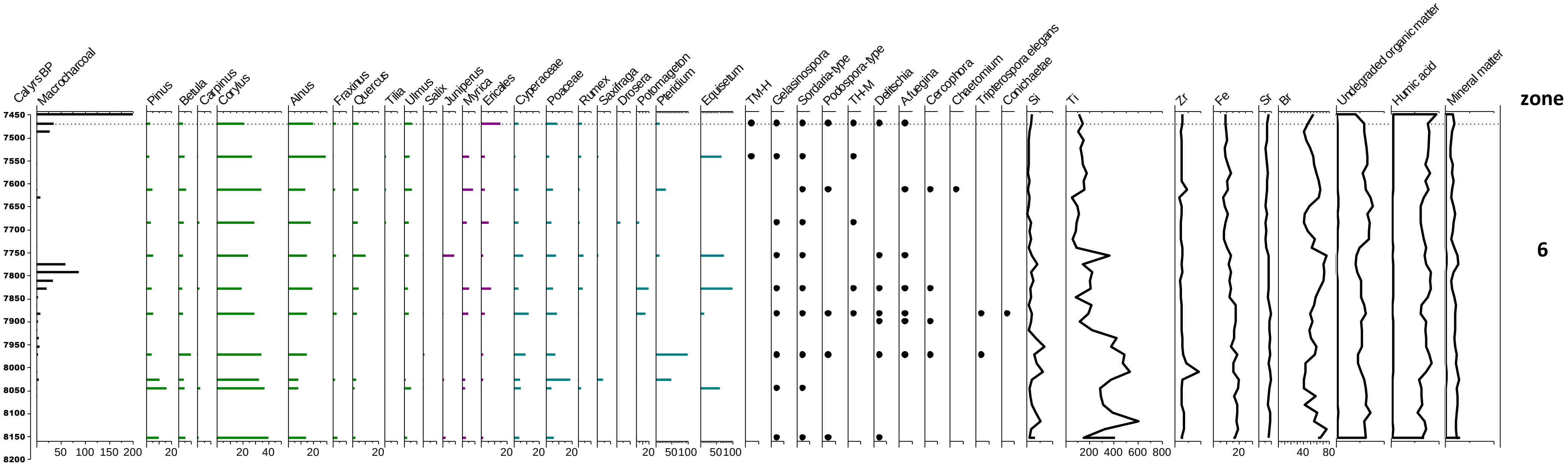


Figure 5-8: Charcoal, pollen, elemental, organic, inorganic and mineral matter diagram for Zone six showing macrocharcoal (area mm^2/cm^2/yr^{-1}) with selected pollen percentages, NPP conc. (count/cm^3), NIRS (ppm) and elemental data (ppm) (Grimm, 2010).

Zone 5 (7470 – 7200 years BP)

This relatively short time period is dominated by major local fire events over a 150 year period (Figure 5.9). These fire events have a notable effect on the soil conditions and the local fungal assemblage. After these fire events there is a change in the assemblage of NPPs present in the sediment. NPPs showing the presence of rotting wood such as *Tripterospora* elegans and *A. fuegina* are not seen after the fire events around 7200 years BP. Fungal spores indicating dung fungi, *Podospora* and *Sordaria* are present during this time of intense local fire events. This could indicate an opening of the area due to the fires making it more attractive to grazing herbivores. The fire events could be ignited by human activity, particularly as *Corylus* reduces during this time. Mesolithic tribes could be hunting and foraging using fire to extend natural openings at the treeline. Alternatively, they could be natural fires ignited by lightning. Type 496, seen in this record at the boundary of zones five and four, has been suggested by Cugny (2010) to be present during wet/dry transitions.

Zone 4: Transition from base-rich to bog conditions: (7200 – 6580 years BP)

After 7200 yrs BP, a shift in the vegetation assemblage occurs, with an expansion of *Calluna vulgaris* and a reduction in Poaceae. Fire events are still present although they do reduce in magnitude after 7050 yrs BP. The NIRS results show that the peat sediment prior to the fire events was highly humified. This could indicate a shift to drier, warmer climatic conditions suitable for fire to occur. The sharp rise in humic acid shown in the NIRS results in figure 5-7, could indicate that the deposition of charcoal fragments particularly at the edge of the peat bog, increased waterlogging which can enhance the acidic conditions and subsequently growth of the peat bog. This would imply that fire events can have a substantial, local effect on a peat ecosystem. The shift between a period of fire to a period of reduced fire could indicate a shifting pattern of wetter to drier conditions. Wetter conditions would lead to an increase in biomass and if followed by drier conditions, this vegetation could then burn. This has also been shown to have occurred in sediments of a similar age in other studies such as Innes *et al* (2013) and Blackford *et al* (2006). Increased openness at the treeline would provide conditions suitable for local fauna such as Red Deer, a prey attractive to Mesolithic tribes for hunting. The ecosystem could very well have been manipulated by people, enhancing the change from base sediment conditions to more acidic conditions with a subsequent expansion of *Calluna*. However, this could have been a natural succession that would have happened irrespective of disturbance events.

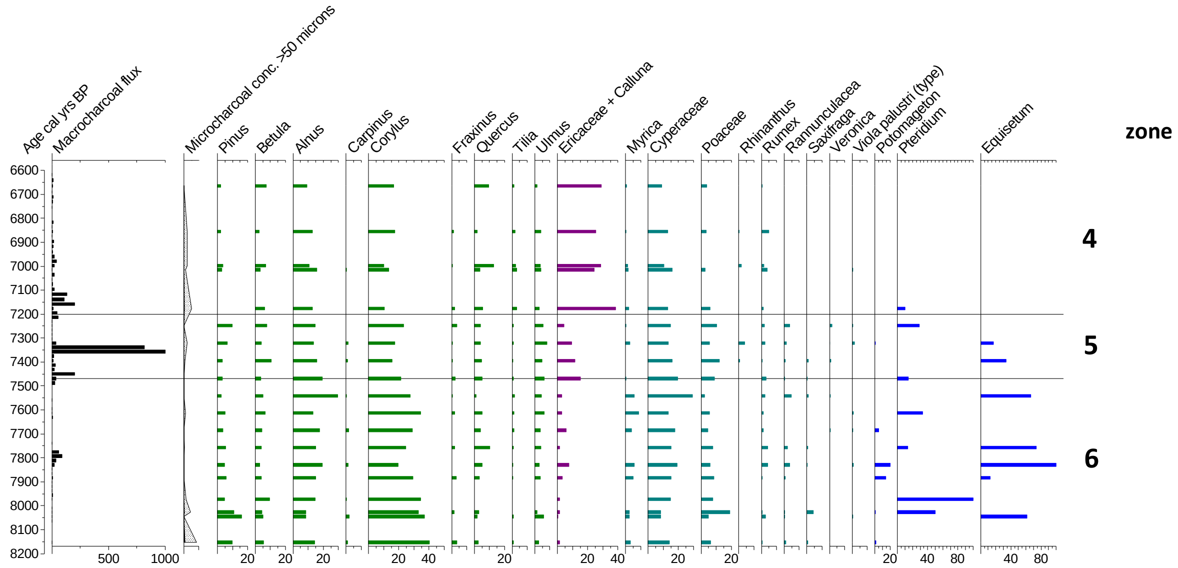


Figure 5-9: Charcoal and pollen diagram (Grimm, 2011) showing macrocharcoal flux, microcharcoal conc. And a selection of pollen percentages and spores for zones six, five and four.

Post 7200 yrs BP, there is a re-establishment of *Calluna vulgaris* (figure 5-9), which was already part of the ecosystem from 8500 years BP as found by Tallis (1990). Trees levels remain low but constant during zone four. The herb species typical of a wet woodland disappear at the same time as the increase in Ericaceae. From 6500 years BP, a change is seen in the fungal spore assemblage with the onset of *Meliola ellisii* and *Isthmospora spinosa* (figure 5-10*)*, a parasite and hyper parasite of *Calluna vulgaris* (Van Geel & Aptroop, 2006). This indicates the local presence of *Calluna* on the bog probably growing on hummocks. See figure 5-10 below.

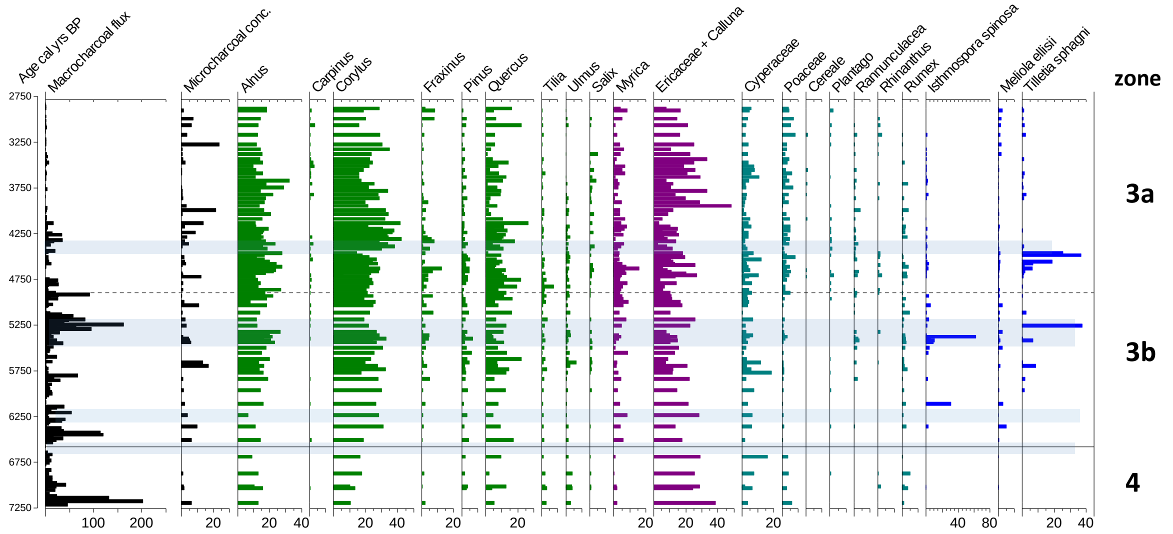


Figure 5-10: Charcoal, pollen and fungal spore diagram showing charcoal flux, charcoal conc. and a selection of pollen percentages and fungal spores.

Figure 5-11: Isthmospora spinosa (hyperparasite of Calluna vulgaris) image taken by Karen Halsall.

Zone 3b (6580 – 4900 years BP)

Zone 3b shown in figure 5-10, covers around 1600 years and represents a relatively stable period dominated by tree taxa and is a time zone showing a high number of local fire events (macrocharcoal record) and also periods of high regional fire evidenced by the microcharcoal record. Ericaceae (including *Calluna vulgaris*) shown in figure 5-10 above*,* reduces from the higher percentage value seen in zone four, whilst *Fraxinus* and *Pinus* increase. An increase in *Pinus* is also seen in Tallis (1990) at Robinsons Moss and discussed as an indication of colder conditions. S*alix* and *Alnus* increase in percentage values during time periods of reduced fire events. Similar to earlier millennia, this indicates a shift between wet and dry conditions. *Salix* shows a series of peaks that are significantly correlated with fire events. *Calluna* is still present locally, evidenced by *Meliola ellisii* and its hyper parasite, *Isthmospora spinosa* (figure 5-10 and 5-11). Heather taxa could be the locally burnt vegetation present on the expanding peat sediment. Correlation of tree species with the microcharcoal record could indicate a lowering of the treeline and fires occurring further away from the site of extraction. Local openness is also indicated by the fungal spore assemblage (figure 5-8). Fungal spores, indicative of tree rot such as T. elegans and A. fuegina (Raynor and Boddy, 1988; Van Geel, 1978, 2001) present in zones six, five and four, are not present in zone three a or three b; however, there is *Podospora* which would suggest the presence of dung from grazing animals such as deer and wild pig. Consistent levels of undegraded organic material and mineral matter with decreasing levels of humic acid shown in figures 5.6 and 5-8 indicates established acrotelm and catotelm layers in the peat. This would also agree with a period of expanding peat sediment and with the local presence of *Calluna* and other heather species, a retreating treeline down slope.

Zone 3a: Colder conditions with lowering of treeline (4900 – 2850 years BP)

Regionally, tree taxa are present with increases in *Alnus* and *Salix* during periods of reduced macrocharcoal similar to zone three b (figure 5-10) which could indicate the continuing shift between wet and dry conditions. A reduction in local fire events is indicated by reduction in the level of macrocharcoal quantities around 4200 years BP, with fire frequency reducing to ~ 4 per 1000 years (FRI below 200 years). Ericaceae increases around 4000 years BP probably due to the reduced number of local fire events. Microcharcoal levels indicate a continuation of fires in the region around Robinsons Moss. Increased disturbance in the region is shown by presence of *Plantago,* Chenopodiaceae, Ranunculaceae and *Rumex* species.

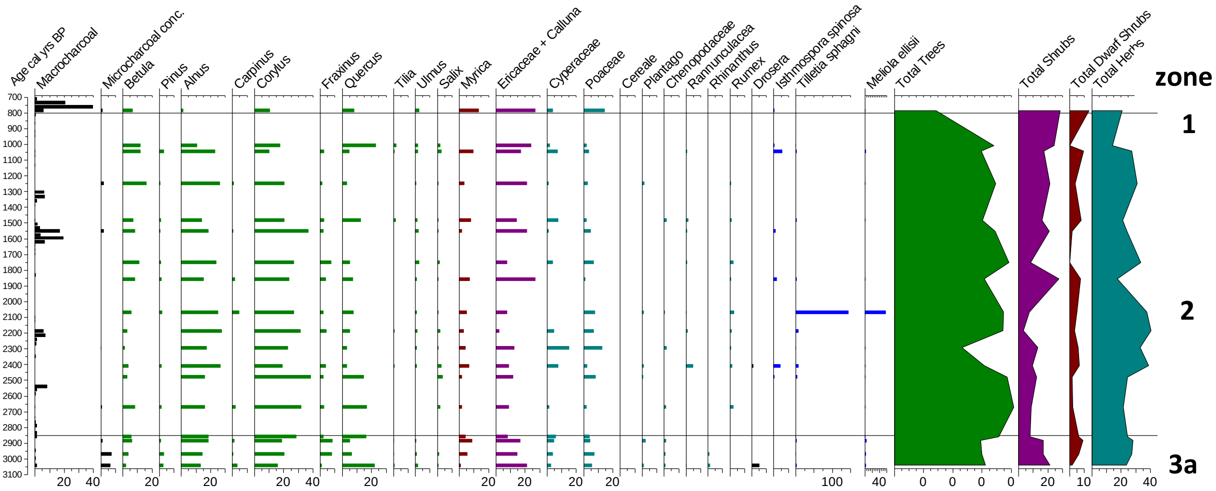


Figure 5-12: Charcoal, pollen and fungal spore diagram (Grimm, 2011) showing macrocharcoal flux with a selection of pollen percentages and fungal spore conc. for zones 1, 2 and part of 3a (Grimm, 2010).

Zone 2: open bog with wet/dry climatic shifts (2850-800 years BP)

During zone two there is generally a low number of fire events, both locally and regionally (figure 5-12). This is thought to be a time period of wet, cold conditions. Major wet shifts have been identified in studies such as those in Charman *et al* (2006) at 2760 and 1600 years BP. The pollen concentration was lower during this zone than in zone three. This is probably a stable environment with an established peat bog and tree taxa on the lower slopes although there could be some local presence of *Alnus, Betula* and *Corylus*.

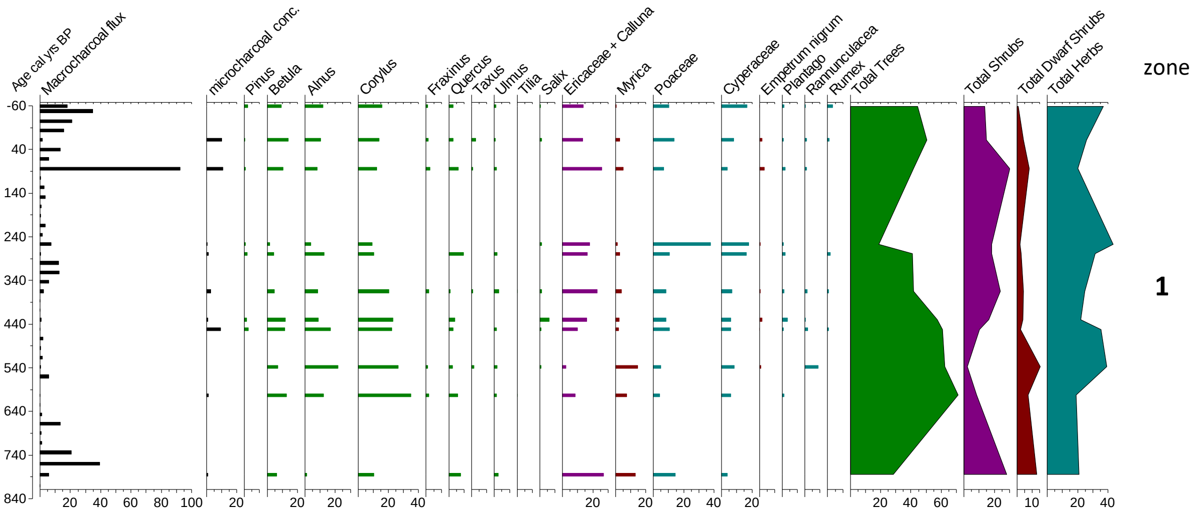


Figure 5-13: Charcoal and pollen diagram (Grimm, 2011) showing macrocharcoal flux, microcharcoal conc. with a selection of pollen taxa (pollen percentages) for zone 1.

Zone 1: Open bog with resurgence of local and regional fire events (800 years BP – present)

Tree taxa reduce during the recent millennia (figure 5-13) although tree percentages increased during the last 100 years and remain present in the region. Currently Robinsons Moss is treeless although some *Betula* can be found near to the Moss at lower altitudes. Relatively small conifer plantations are nearby. A peak in Poaceae can be seen around 300 years BP probably reflecting a peak in local sheep grazing. Heather species remain in the area particularly during the last 100 years. *Calluna* is a locally dominant species used as a food source for grouse with prescribed fire as a management strategy used to promote the growth of young shoots as a food source.

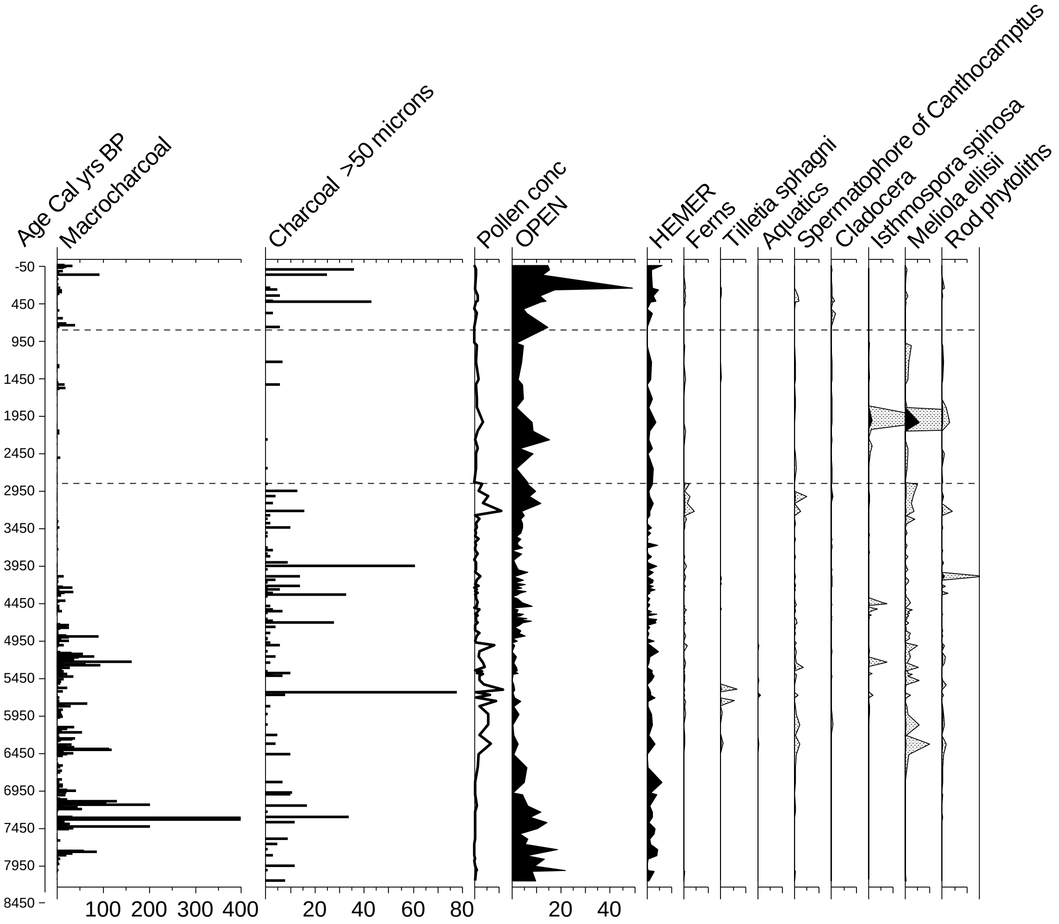


Figure 5-14: Charcoal, pollen, spore and NPP diagram (Grimm, 2011) showing a selection of botanicals. OPEN is a variable sum of pollen percentages for taxa representing landscape openness. HEMER is a variable sum representing hemerophilous and cultivation taxa (Reitalu, 2013).

Taxa associated with human activity are included in the HEMER variable (*Cerealia, Plantago, Artemisia* and *Rumex*) and taxa associated with landscape openness are included in the OPEN variable (*Juniperus, Cerealia,* Poaceae*, Plantago, Typha, Artemisia* and *Filipendula*) as shown in Reitalu *et al* (2013). Compared together, these variables indicate (figure 5-14) that there could have been human activity from 8200 – 7000 years BP and also during the last 800 years. The increase in openness from 3000 to 2000 years BP does not correspond to higher values in the HEMER variable with the implication that this time period is more likely to be a more open landscape due to a change in climatic conditions.

5.6.5 Statistical results

There are many techniques that can be employed to provide statistically robust information for the interpretation of multiproxy data in terms of fire – vegetation relationship. Below is a selection of these techniques used with the data for Robinsons Moss.

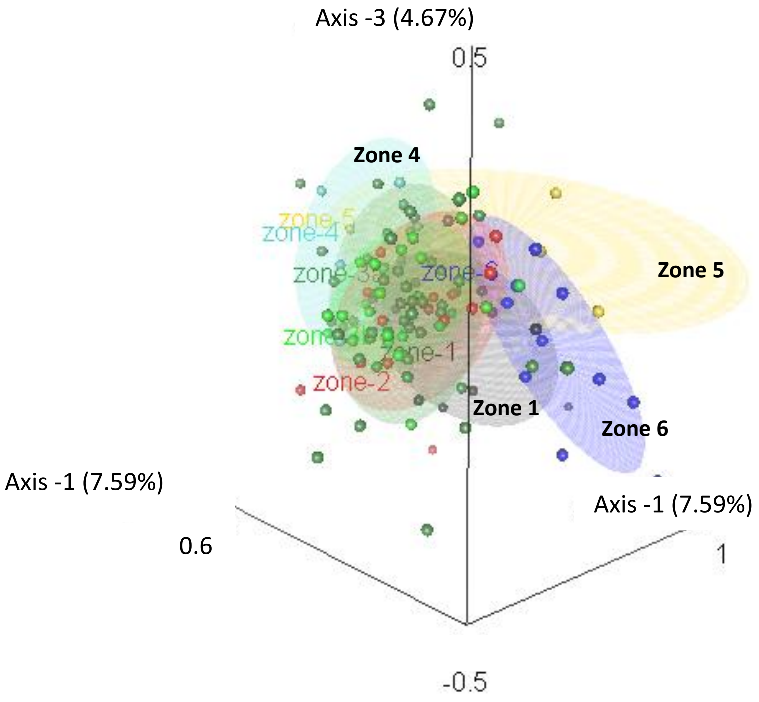


Figure 5-15: 3D plot showing how the vegetation zones defined by CONNIS (Grimm, 1987) are distributed along the first three DCA axes.

Figure 5.15 shows the temporal trends of the vegetation zones defined by CONNIS (Grimm, 1987) as influenced by the first three environmental drivers DCA1,DCA2 and DCA3 (table 5-1). This shows the influence of these drivers on each zone but doesn't identify what those drivers are. DCA1 has an influence on zones one (black), five (yellow) and six (blue). Zone four is influenced by DCA2 and DCA3. The remaining zones show a complex mix of drivers. Detrended Correspondence Analysis is useful to identify differences between vegetation zones.

	DCA1	DCA2	DCA3
RDA1*100/tot. inertia	7.59	7.27	4.67

Table 5-1: Percentage of variance (RDA1*100/total inertia) explained by charcoal (as a constrained variable) assigned to the first three DCA axes.

Redundancy Analysis

Using charcoal fragments as the explanatory variable, the species scores shown on Principal Component one (PC1) have been divided into seven vegetation zones and plotted separately against microcharcoal conc. and then macrocharcoal flux in both cases using charcoal as the explanatory variable RDA1. Introducing fire into the model will show how much variance is explained by charcoal abundance (as an indication of temporal changes in fire events) for each of the vegetation zones (figure 5-16).

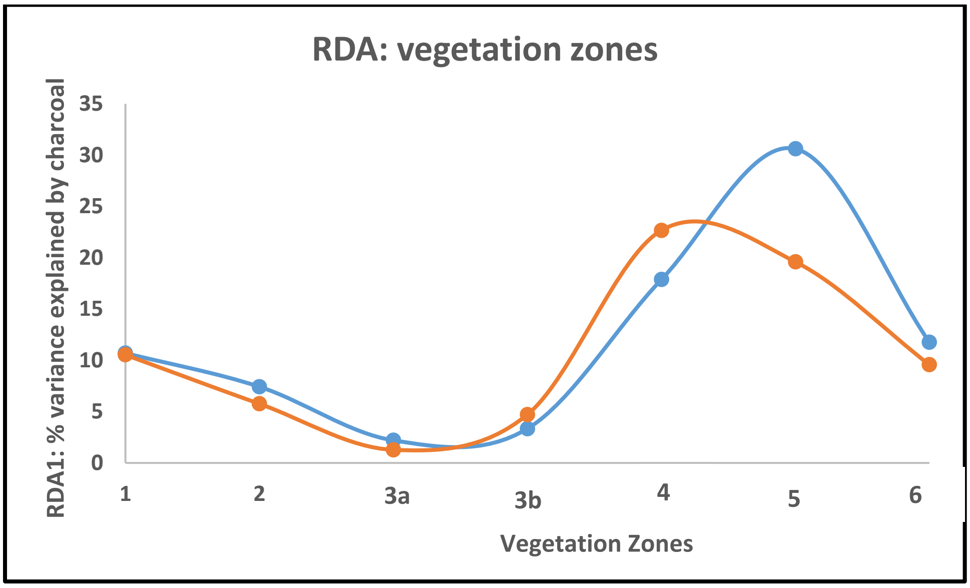
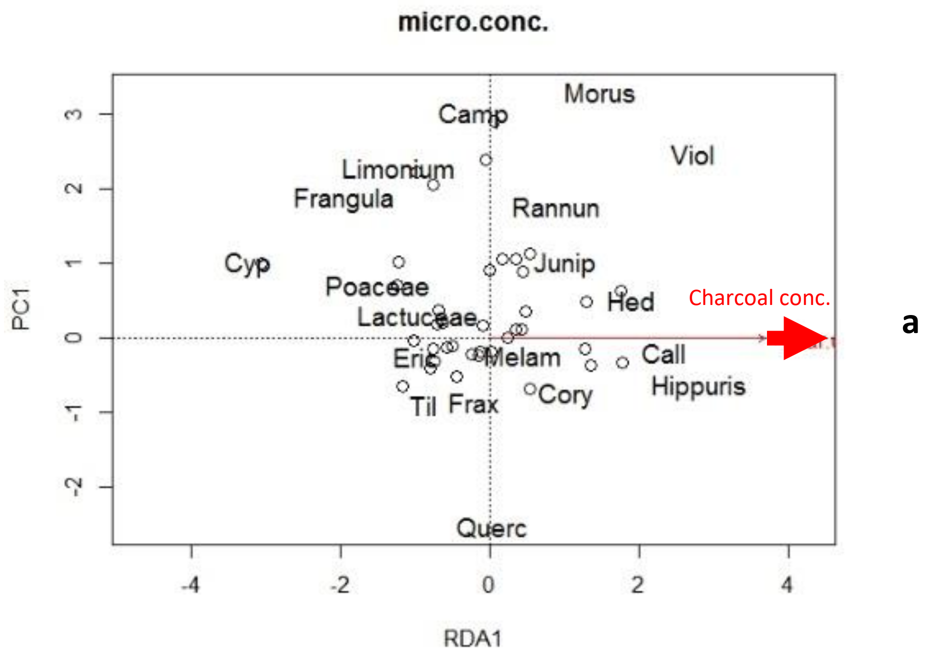


Figure 5-16: Variance (RDA) within the vegetation assemblage for each zone using charcoal as the constrained variable; microcharcoal (orange line) and macrocharcoal (blue line).

Fire – vegetation relationship

Redundancy analysis can also indicate the strength and direction (positive or negative) of the relationship between taxa and fire. See figure 5-17 a and b and table 5-2. Dividing the pollen record into zones and calculating RDA values with charcoal as the explanatory variable, we can see in the plots for each zone in figure 5.16 above the changing relationship of dominant taxa with charcoal, both microscopic and macroscopic charcoal. For example, *Calluna vulgaris* tends to expand with medium levels of microcharcoal in zone four and five (diagrams are in annexe 1). *Quercus* tends to be disadvantaged at low, medium and high levels of charcoal fragments.



Macro flux

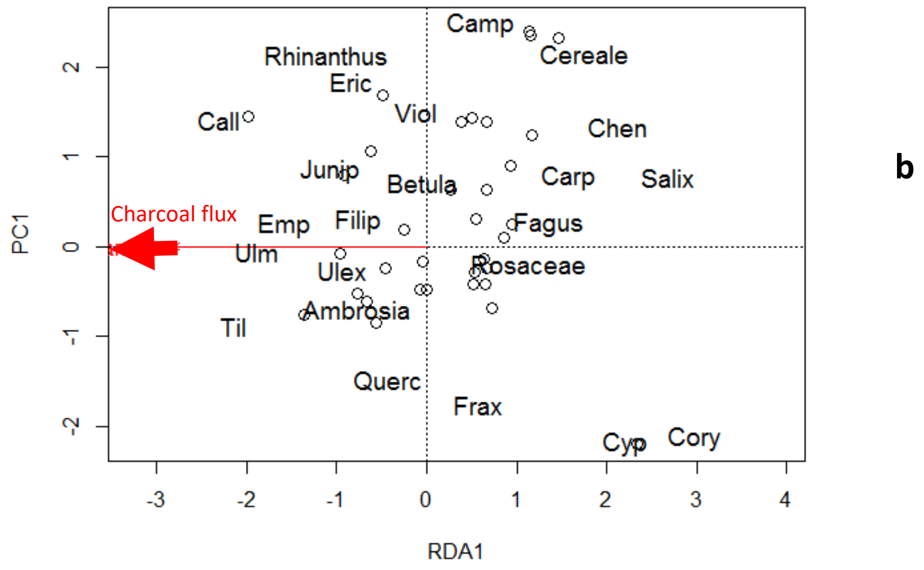


Figure 5-17: RDA values plotted with charcoal fragments as a constraining variable showing the temporal relationship of dominant taxa with increasing charcoal abundance. RDA values were calculated using the VEGAN package in R (Oksanen *et al*, 2018); microcharcoal conc. (a) and macrocharcoal flux (b).

Figure 5.17 b shows that *Calluna* expands with high charcoal levels highlighting the adapted relationship that this dominant shrub has with fire. *Tilia* has a negative relationship with both micro and macro charcoal. *Quercus* has a negative relationship (micro and macro) with medium charcoal abundance.

Positive with high charcoal values	Positive with medium charcoal values	Positive with low charcoal values	Negative with high charcoal values	Negative with medium charcoal values	Negative with low charcoal values
Calluna	*Betula*	Chenopodiaceae	*Ulmus*	*Pinus*	*Corylus*
	Poaceae	*Salix*	*Tilia*	*Fraxinus*	
	Ericaceae			*Quercus*	
				Rosaceae	

Table 5-2: Relationship of a selection of pollen taxa with macrocharcoal.

The percentage of variance in the vegetation dynamics explained by fire (RDA) was calculated for the entire core as a value of 0.633%. As the relationship of vegetation with fire will change over different millennia, a more informative value can be calculated using a moving window. For Robinsons Moss this value is 11.12 % over the complete record and the range is 4.33 to 16.38 % for the macrocharcoal record. So, for the whole dataset, fire still only explains a small proportion of the variance. In the Swiss Alps, Colombaroli (2010) found that the overall percentages variance was 8.4 - 32.2% and that climate was the dominant driver. For Robinsons Moss, this also implies that there are factors other than fire driving the ecosystem. So what are these factors?

RDA values using the moving window technique are shown in the two plots below, 5.18.a (macrocharcoal) and 5.18.b (microcharcoal).

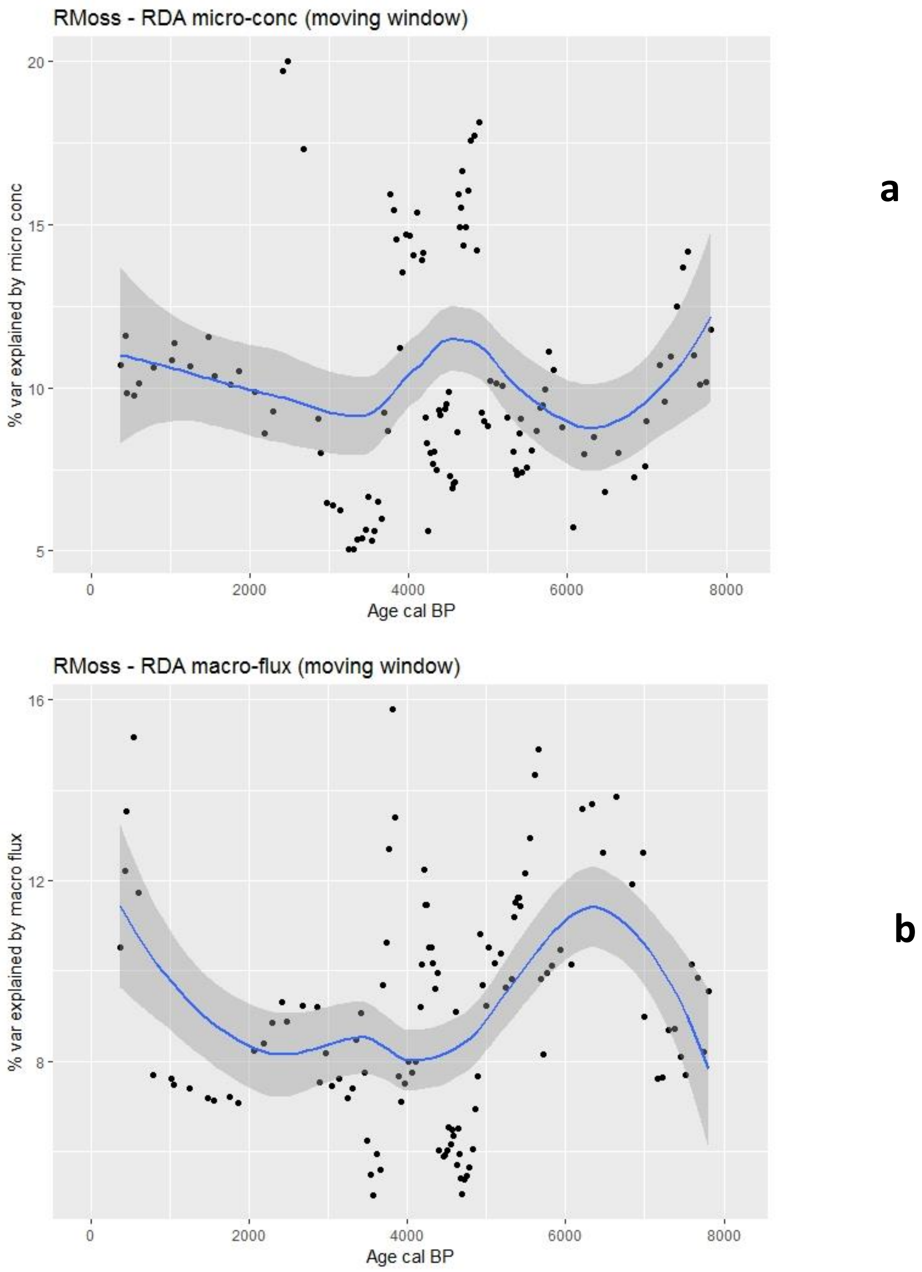
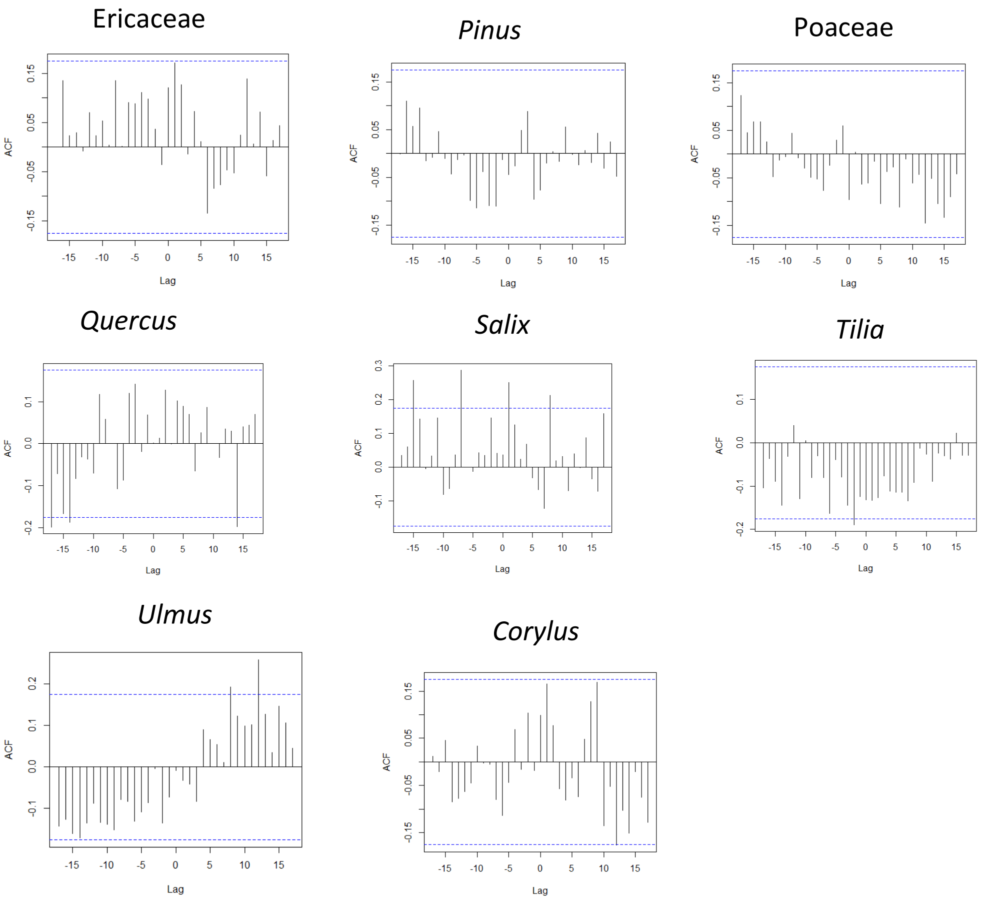


Figure 5-18: RDA showing % variance of vegetation (inferred by pollen) explained by fire (inferred by macrocharcoal (a); microcharcoal (b)) calculated using the VEGAN package in R (Oksanen et al, 2018). Points represent RDA values using a moving window (10), blue line obtained using a loess smoothing function (span = 0.3), and shaded areas represent 95% confidence limits.

Although the variance explained by fire is similar in RDA value range for macrocharcoal and microcharcoal, there is a temporal difference in the major peak for the records. For macrocharcoal (figure 5-18a), this occurs between 7000 – 6000 years BP and for microcharcoal (figure 5-18b), this occurs 5000 – 4000 years BP. This difference can be further explored by looking at correlations between individual taxa and more detail in the macrocharcoal and microcharcoal records. If the record is divided into the vegetation zones and the response data for both macro and microcharcoal are shown together, then the variance explained by fire is very similar for both macro and microcharcoal except for the major peak in macrocharcoal values at around 7300 years BP (figure 5.16). Analyses were carried out using the statistical software R (version 3.4.3 R Development Core Team 2017).

Microcharcoal

Microcharcoal is usually interpreted as representing regional fire and even fire from thousands of kilometres from the extraction site and consequently is more difficult to interpret. Cross-correlation analysis can add useful insight into fire-vegetation dynamics as it shows the long term effect of fire on vegetation by showing the lag effect between taxa and charcoal fragment abundance. The Kendal's tau value used in this analysis adjusts for the data being non-parametric.



Ericaceae

Pinus

Poaceae

Quercus

Salix

Tilia

Ulmus

Corylus

Figure 5-19: Microcharcoal (>50 microns) cross-correlated with a selection of pollen taxa. The horizontal axis shows the lag time (yrs) since a fire event at lag 0 (correlation value) in 50 year steps and the vertical axis is an estimation of the cross correlation coefficient (R version 3.4.3 R Development Core Team 2017).

Tilia has a consistently negative relationship with microcharcoal, although only significant at a lag of 100 years. Ericaceae has a mostly positive relationship with microcharcoal. This is not shown as significant in the cross-correlation analysis above (figure 5-19). Poaceae has an interesting relationship with fire. It is a positive relationship until the major fire period 7200 – 7050 years ago after which, it displays a mostly negative relationship. This can be seen in figure 5-20 where high Poaceae percentages correspond with low microcharcoal values between 8000 – 7000 years BP whereas during the last 800 years, high microcharcoal values correspond with high Poaceae percentages. High Ericaceae abundance mostly corresponds with low microcharcoal values (except from between 2500 – 800 years ago).

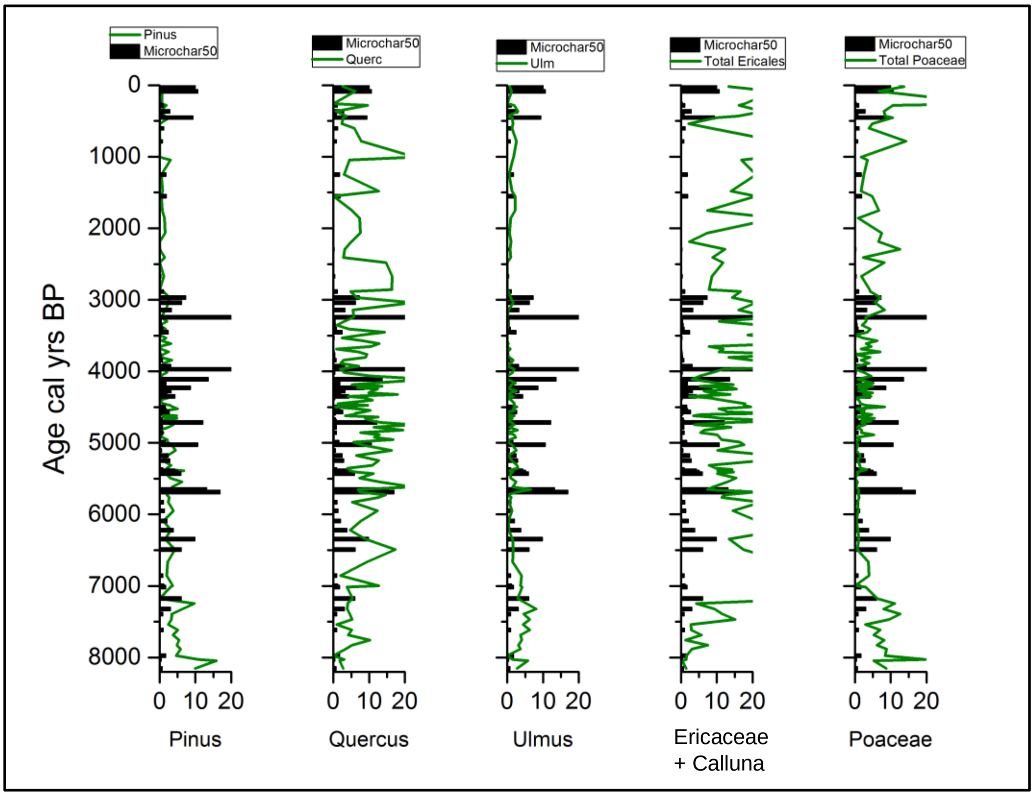


Figure 5-20: A selection of pollen taxa percentages (green lines) against age years BP shown with microcharcoal flux values (black bars).

Table 5.3 below shows the correlation between microcharcoal (> 50 microns) with a selection of taxa. This shows different results in that *Alnus, Calluna* and *Betula* are significantly correlated with microcharcoal, with Ericaceae significantly correlated at the time of a fire event shown in the cross-correlation. *Pinus*, *Quercus* and Poaceae are not correlated, but *Salix*, *Ulmus* and *Corylus* are correlated at a lagged time from the fire event using the cross-correlation technique. However, microcharcoal peaks occur between 5500 to 3000 year BP and it is during this time that *Quercus* and Ericaceae (including *Calluna*) respond to regional fire events (see figure 5-20).

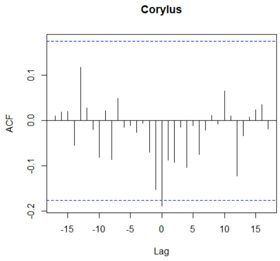
Taxa	**Tau**	**P value**	**significance**
Canthocampus	0.0194	0.765	non sign.
Cladocera	0.00868	0.9032	non sign.
Pinus	0.04629	0.4677	non sign
Quercus	0.0206	0.7443	non sign
Poaceae	0.01353	0.8307	non sign
Alnus	- 0.1796	0.00466	**
Calluna	0.1274	0.04373	*
Betula	0.9666	0.00264	**
Ulmus	-0.02302	0.7199	non sign.
Tilia	0.04098	0.5324	non sign.

Table 5-3: Correlations between microcharcoal > 50 microns and a selection of taxa and NPPs using Kendall's Tau calculation and showing associated p values. 95% (*), 99% (**).

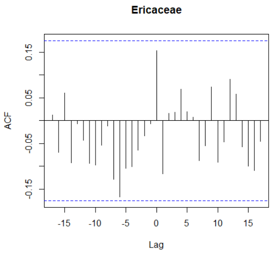
Macrocharcoal

For lacustrine sediments, macrocharcoal is usually interpreted as representing local fire events within 1 Km of the extraction site (Carcaillet *et al*, 2001) although it can also have travelled from up to tens of kilometres away (Whitlock *et al*, 2010). Macrocharcoal found in bogs is thought to represent a charcoal source area between 1 – 4 km (Carter *et al*, 2018).

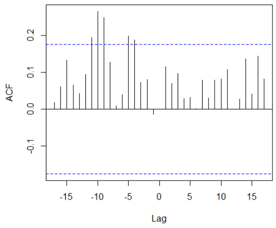
Corylus



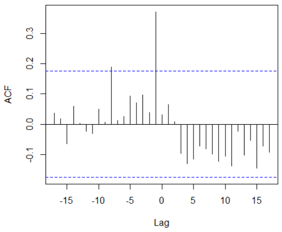
Ericacea



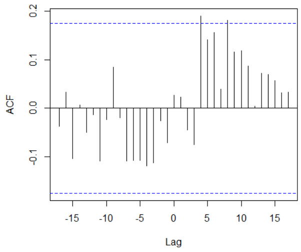
Pinus



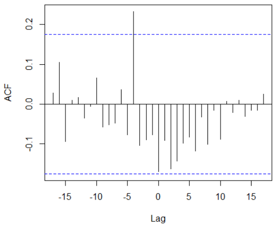
Poaceae



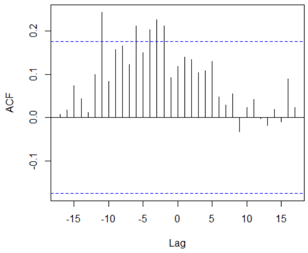
Quercus



Salix



Ulmus



Tilia

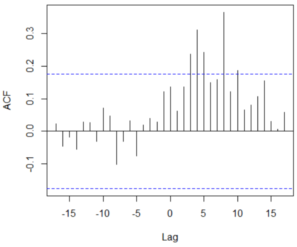


Figure 5-21: Macrocharcoal (>180 µm) cross correlated with a selection of pollen taxa. The horizontal axis shows the lag time (yrs) since a fire event at lag 0 (correlation value) in 50 year steps and the vertical axis is an estimation of the cross correlation coefficient (R version 3.4.3 R Development Core Team 2017).

Figure 5-21 shows *Pinus* has a consistently positive relationship with macrocharcoal. *Corylus* has a significant, mostly negative relationship with macrocharcoal. *Pinus* shows consistently positive correlation values that is significant at a lag of around 250 years. *Ulmus* and *Tilia* are both significantly positively correlated with the long-term absence of macrocharcoal.

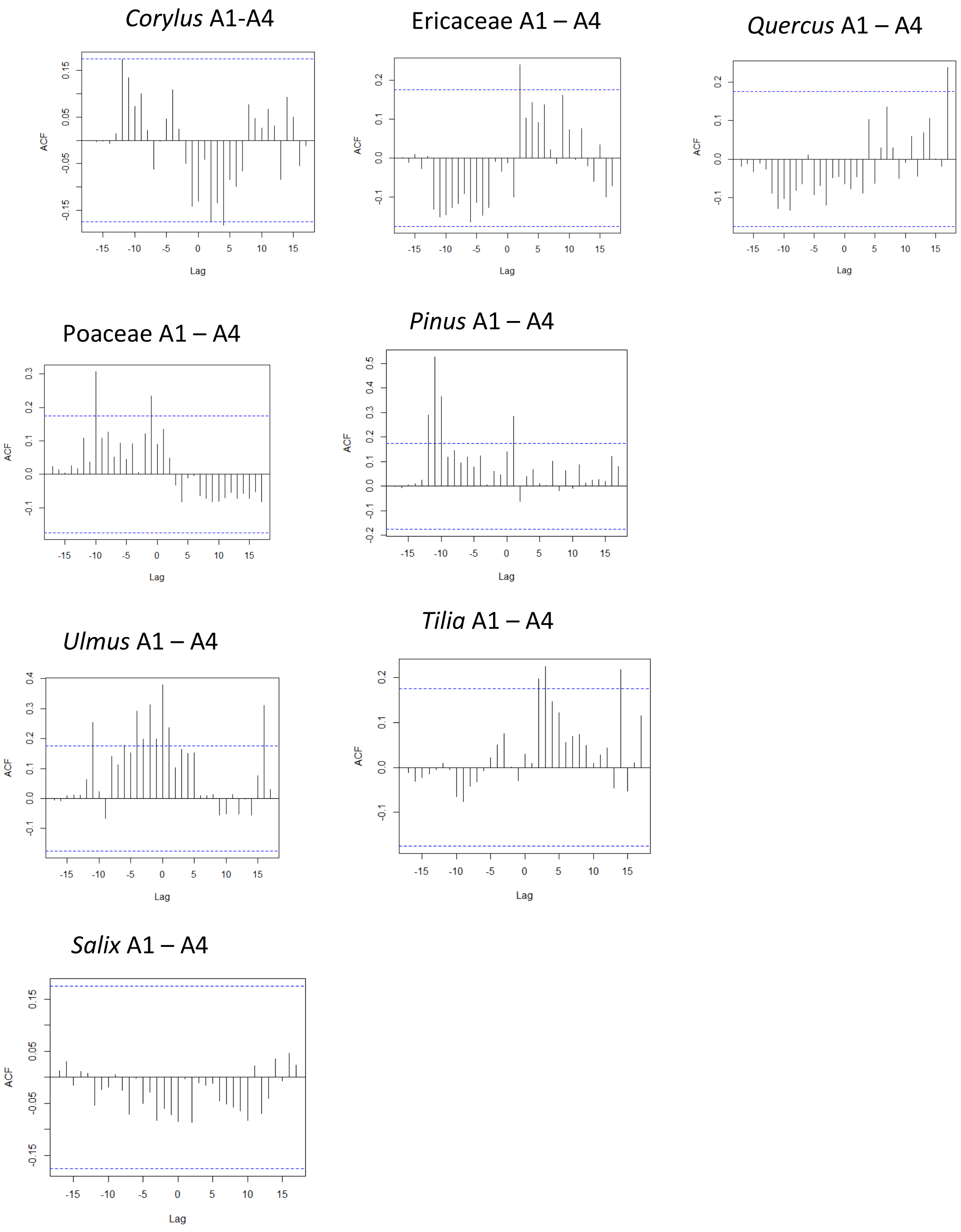


Figure 5-22: Macrocharcoal (>180 microns) for fragments size 180 microns – 2mm (>2mm not included). The horizontal axis shows the lag time (yrs) since a fire event at lag 0 (correlation value) in 50 year steps and the vertical axis is an estimation of the cross correlation coefficient (R version 3.4.3 R Development Core Team 2017).

Removing the larger pieces of charcoal from the analysis shows interesting results for the non- arboreal taxa, Poaceae and Ericaceae. This cross correlation shows that for most of the record, when Poaceae is positive, then Ericaceae is negative and vice versa (figure 5-22). Correlation between macrocharcoal and a selection of taxa using Kendal’s tau is shown in table 5-4. Only *Cladocera* parts, which are a proxy for the presence of temporary water, are significantly correlated with macrocharcoal values.

Taxa	**Tau**	**P value**	**significance**
Canthocampus	0.05143	0.4293	non sign.
Cladocera	- 0.17786	0.01231	*
Pinus	0.0942	0.1372	non sign.
Quercus	0.03396	0.5892	non sign.
Betula	- 0.0334	0.5953	non sign.
Poaceae	0.00636	0.9195	non sign.
Calluna	0.06506	0.2971	non sign.
Ericaceae	0.0476	0.4489	non sign.
Ulmus	- 0.02302	0.7199	non sign.
Tilia	0.1101	0.0309	*

Table 5-4: Correlations between macrocharcoal and a selection of taxa and NPPs using Kendall's Tau calculation and showing associated p values. 95% (*).

This section of chapter four has investigated the differences between correlation of specific taxa with both microcharcoal found on pollen slides (>50 µm) and macrocharcoal (>180 µm). The results have shown that different methods vary in the taxa that are significantly correlated with fire events and so care should be taken in the choice of correlation technique used in studies investigating fire regimes. It is also interesting to see the difference in how macrocharcoal and microcharcoal abundance relate to fire events. This is relevant to this study as the charcoal source area for studies using blanket peat sediments in still a debatable issue.

CharAnalysis

The fire records compiled with macrocharcoal and microcharcoal fragments have been analysed to determine which of the peaks in charcoal fragments are significant. The common programme used for this is CharAnalysis (Kelly *et al*, 2011). This programme can be used to calculate the fire return interval and fire frequency.

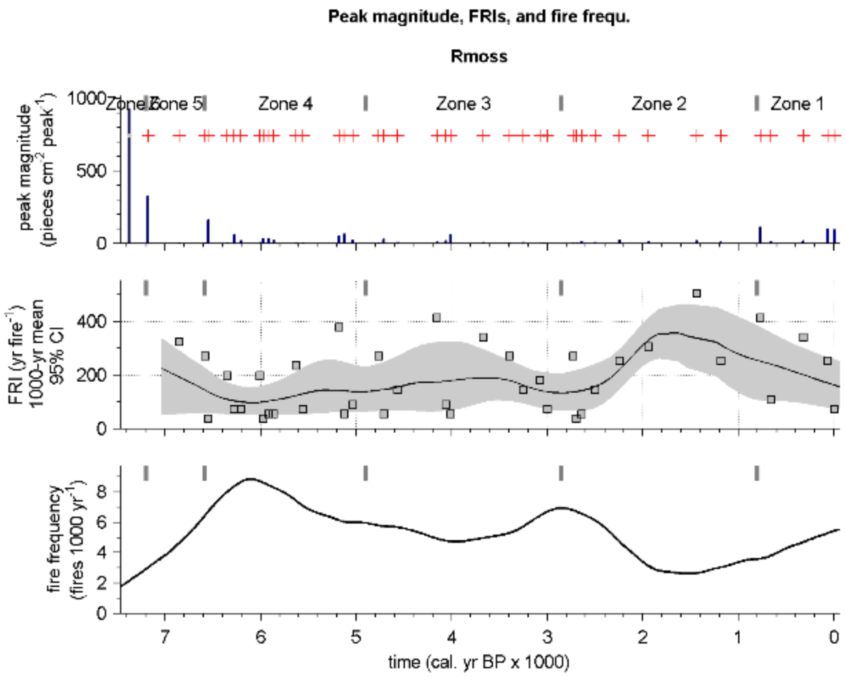


Figure 5-23: Reconstructed palaeofire peaks, fire return intervals (FRI) and fire frequencies using macrocharcoal fragment abundance (count).

The lowest FRI is around 6250 years BP when eight fires per 1000 years occur. This increases to its highest value around 1800 years ago when two fires per 1000 years were occurring. The FRI continued to decline from 1800 years BP to present day and the number of fires increased from two to six during this time (figure 5-23).

Arco

The peaks produced using the CharAnalysis programme used count sums of charcoal fragments. These peaks have been further analysed by screening the charcoal area estimates with respect to the count sums using the ARCO programme (Finsinger, 2014). Peaks in charcoal area quantities can be a more robust measurement of burned biomass than charcoal counts as counts increase if fragmentation is an issue (Leys, 2013). Counts are subject to biases introduced through taphonomy and laboratory processes causing breakages in the charcoal fragments (Halsall *et al*, 2018; Brown and Power, 2013). Plotting the $C_{\#}/C_A$ ratio is one way to investigate the relationship between counts and area quantities (Finsinger *et al*, 2014, Carter *et al*, 2018) and to determine if fractionation is an issue.

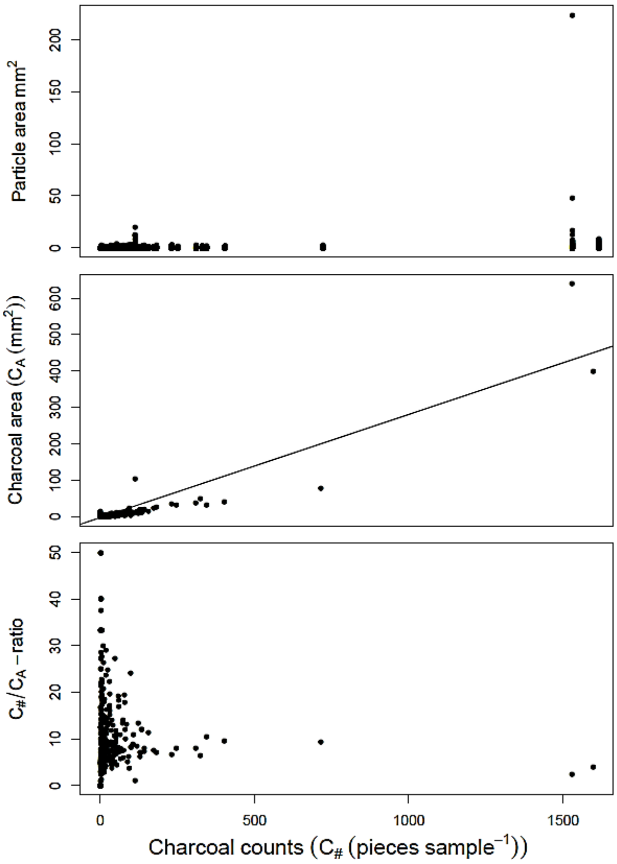
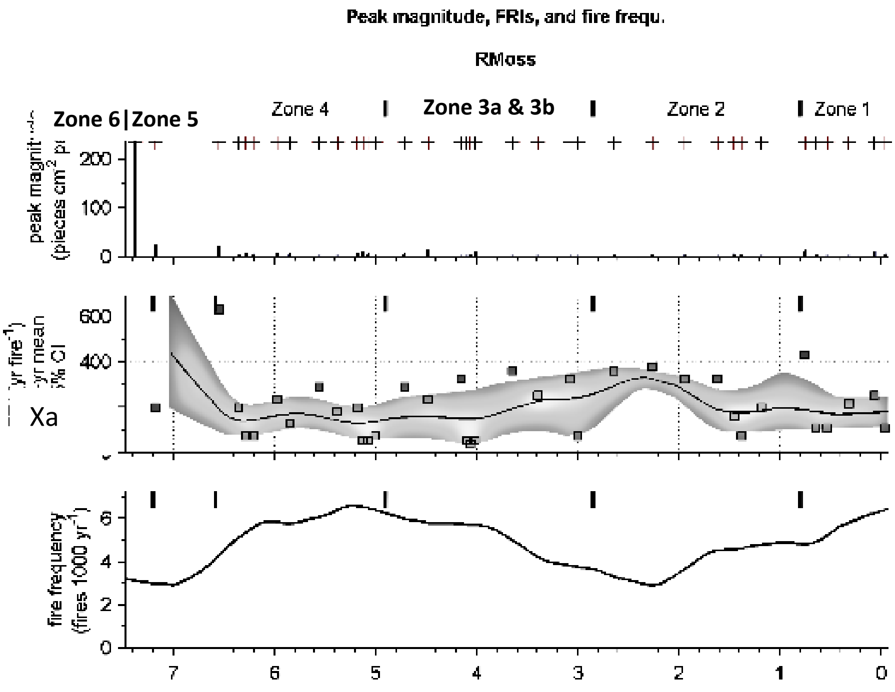
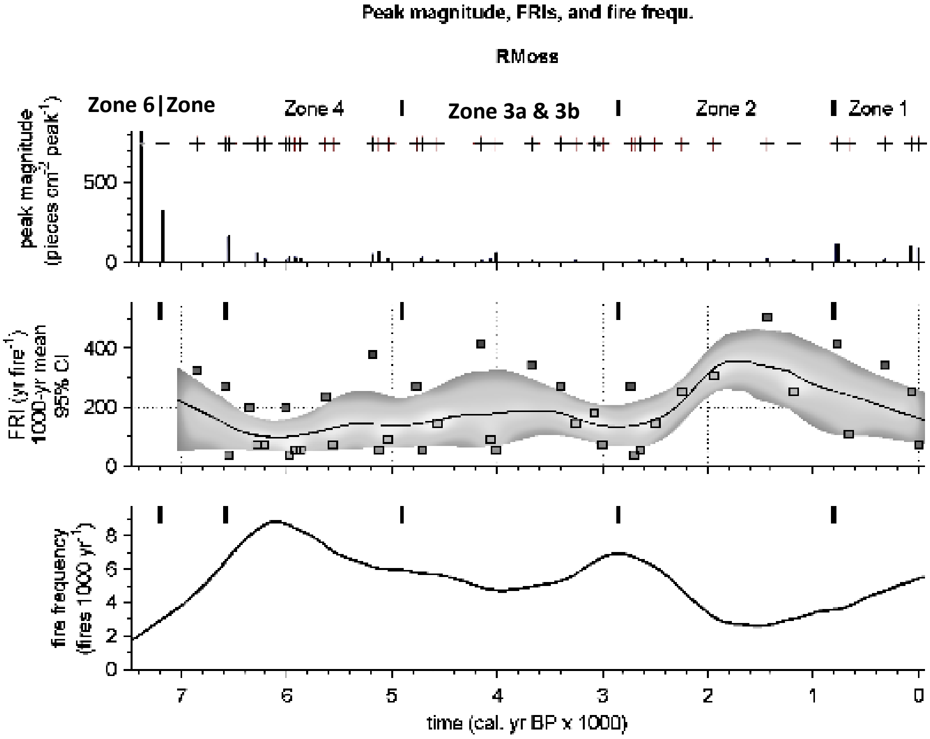


Figure 5-24: Scatter plots showing the relationship between Particle area (mm^2), charcoal area C_A (mm^2) calculated using CharAnalysis and $C_{\#}/C_A$ ratio plotted against charcoal counts $C_{\#}$ (pieces.sample^{-1}) to explore the relationship between count and area to identify charcoal breakages due to taphonomic processes.

Charcoal counts were mostly below 500 with a few outliers above 1500 counts. Generally, samples with the highest $C_{\#}/C_A$ ratios had smallest charcoal counts suggesting that taphonomic bias due to breakage was negligible for Robinsons Moss (Finsinger *et al*, 2014). This is shown in figure 5-24.



A: Char$_A$



B: Char$_C$

Figure 5-25: Standard CharAnalysis graphs showing; peak magnitude (pieces cm^3 peak $^{-1}$), fire return interval (FRI) (1000 yr mean fire^{-1}). Grey area representing 95% C.L. and fire frequency (fires 1000 yr^{-1}). All are plotted against Age (cal yrs BP x 1000) for Charcoal area, CharA (A) and charcoal count, CharC (B). Fire zones defined by CharAnalysis.

Char$_C$ (figure 5-25 B) identified 42 peaks in charcoal fragments and Char$_A$ (figure 5.25 A) and screened Char$_A$ identified 37 peaks. Both records showed a higher fire frequency from 7000 – 3000 years BP than 3000 – present day although Char$_A$ showed a reduction in fire frequency 5000 – 4000 years BP which is not shown in the Char$_C$ record. Both records showed high magnitude fires from 7500 – 6600, lower magnitude fires from 4000 – 800 years BP and an increase in magnitude and fire frequency over the last 1000 years BP. Both records show a higher fire FRI from 7500 to 6500. Char$_A$ shows a higher FRI than Char$_C$ from 2000 – 1000 years BP. This time period thought to be wetter and colder than previous millennia, showed low magnitude fires during this time.

Cal yrs BP	Zone	FRI (Char$_C$)	FRI (Char$_A$)
2850	2	221	243
4900	3	176	190
6580	4	126	141

Table 5-5: Mean Fire Return Intervals (FRI) for zones 2, 3 and 4 calculated using results from CharAnalysis (Kelly et al, 2011).

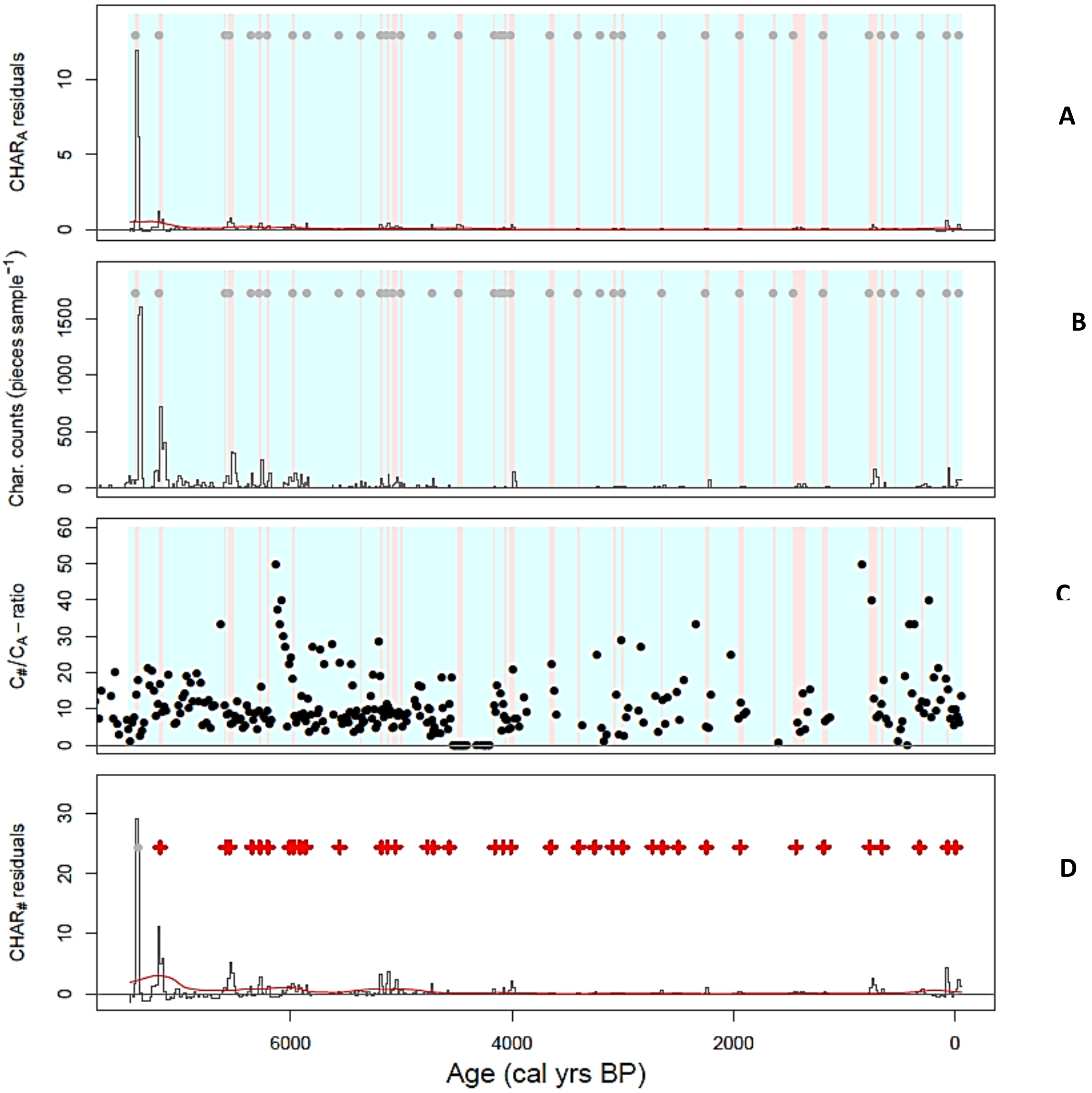


Figure 5-26: Comparison between reconstructed fire-episode histories (A, D) based on charcoal areas and charcoal counts, (B) charcoal-counts (C#) record and (C) charcoal counts/charcoal area ratio (C#/CA ratio). In (A) and (D): grey line – CHAR residuals (CHARi–CHARback); red line – threshold; red crosses – significant charcoal peaks that survived the screening tests (FIRE#sp and FIREAsp runs); grey dots – insignificant charcoal peaks (FIRE# and FIREA runs). Graphs descriptions from Finsinger (2014).

Char$_A$ residuals and Char$_C$ plotted against age (years BP) show similar a similar pattern of charcoal peaks (figure 5-26 A). Two further graphs produced from running the ARCO script can be found in Annexe 1.

Comparison of Charanalysis, Arco and RDA

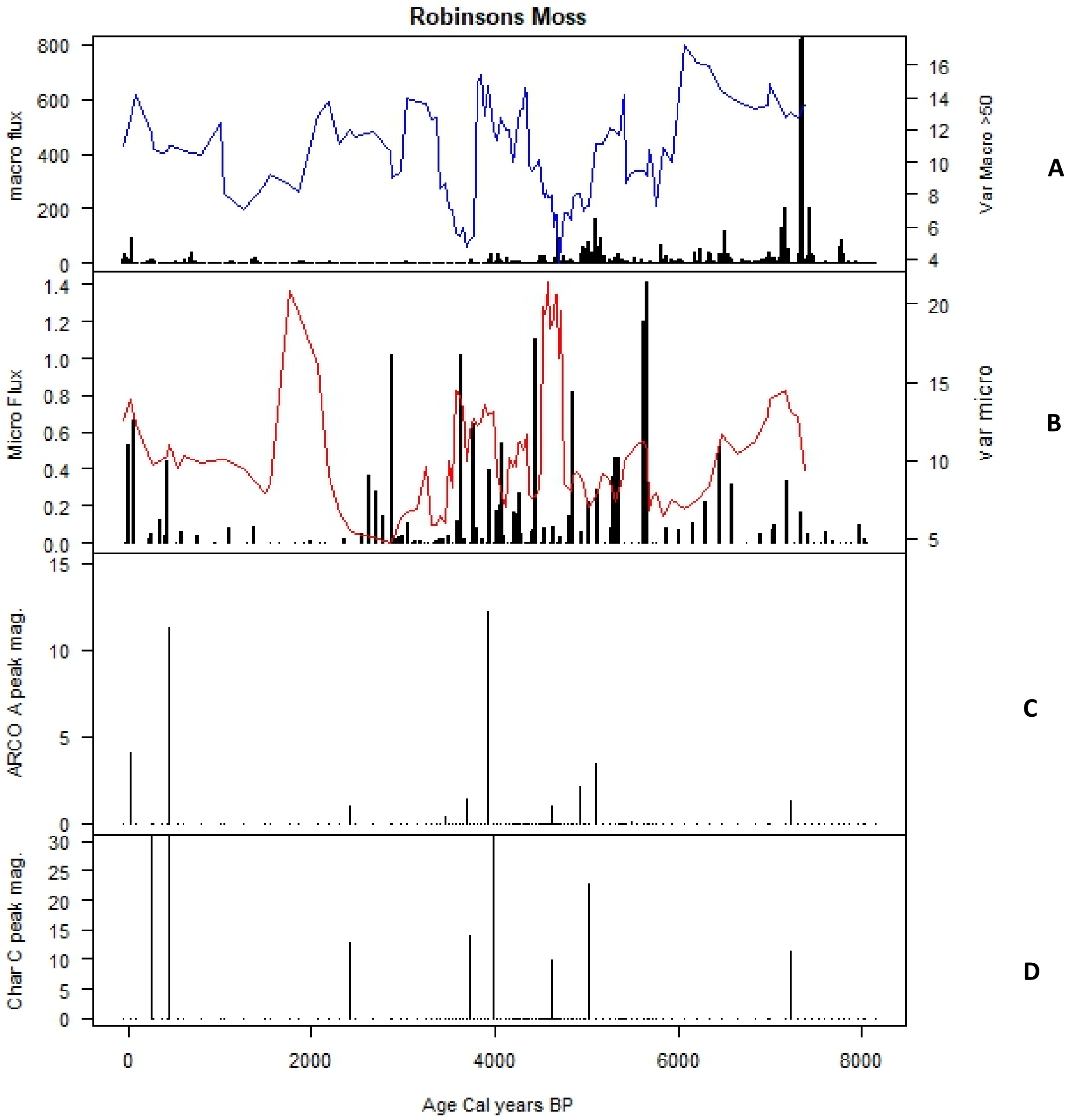


Figure 5-27: Comparison of macroscopic and microscopic charcoal data for Robinsons Moss: RDA values using macroscopic charcoal as constrained variable (blue line) plotted with macrocharcoal area as flux mm^2/cm^3/year (black bars), A; RDA values using microscopic charcoal as constrained variable (red line) plotted with microcharcoal conc. as count/cm^3 (black bars), B; Screened macrocharcoal area peaks using ARCO, C and macrocharcoal count peaks using CharAnalysis, D. All graphs plotted against Age Cal years BP.

Graph A in figure 5-27 shows the impact of regional fire as described by microcharcoal conc. (particles/cm^2) and the impact of local fire as described by macrocharcoal flux (area mm^2/cm^2/yr) over the entire record. The percentage variance in the vegetation dynamics based on macrocharcoal peaks increases during the time period 7478 – 7323 and ~ 6467.

These peaks pass the peak screen test devised by Finsinger *et al* (2014) shown in graph 5-27 D. Local fires are also important in terms of vegetation dynamics around 3324 years BP during the Bronze Age time period. Regional fires are also occurring at this time (graph B) and during a prior time period of around 400 years from 4000 – 4400 years BP at which time these fire events also had an impact on the vegetation dynamics. Increased variance in the vegetation dynamics attributed to fire events is also seen around 1600 years BP during the Iron Age. Both local and regional fires are recorded during the last 150 years from around 1850, which is often recorded as the start of the Industrial Age in the U.K. These peaks are also recorded in the datasets 5-27 C and D using the CharAnalysis programme (Higuera, 2014) and the ARCO screening technique (Finsinger *et al*, 2014) respectively.

One of the limitations of the ARCO screening test is that very large local fires (as in the major local fire event period recorded between 7478 to 7323) fail the screening test as they are tested to be so large that they could have occurred randomly. However, by expressing fire events in multiple ways as in figure 5-27 above, this limitation can be accommodated.

5.6.6 Geochemical Analysis

The bottom section of the core was analysed for changes in element abundance (ppm) as this can indicate disturbances such as erosion or fire events (Mackereth *et al*, 1996). Results are shown in figure 5-28. NIRS analysis was employed to explore changes in the organic and inorganic material within the peat. These results are shown in figure 5-29.

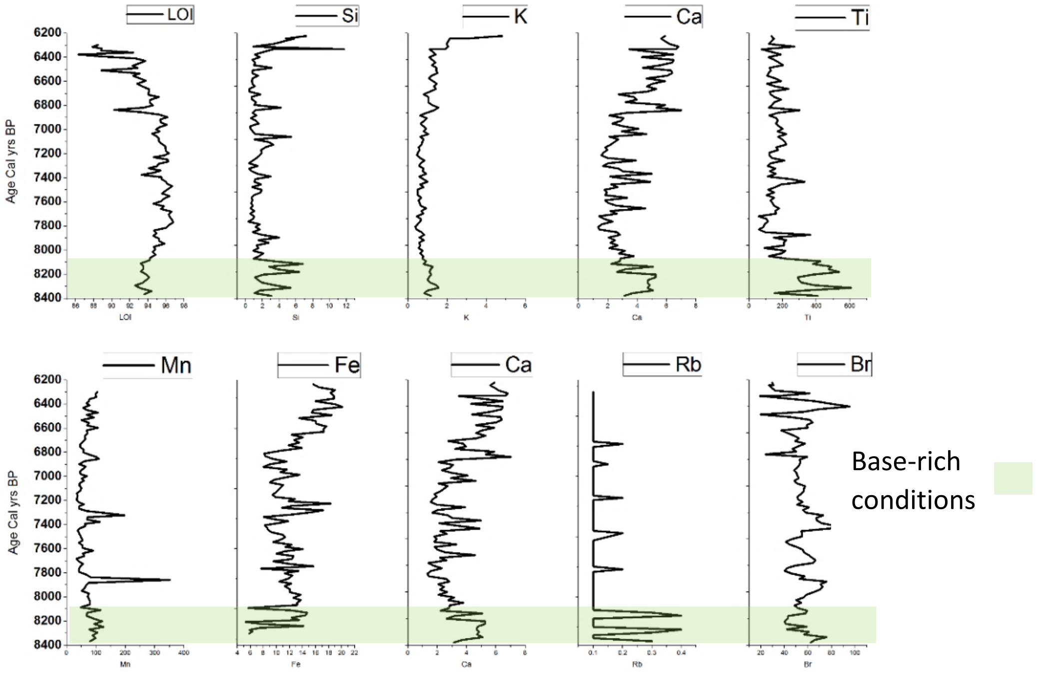


Figure 5-28: XRF analysis for a selection of elements (ppm) (x axis) plotted against Age cal yrs BP (y axis).

5.6.7 NIRS analysis

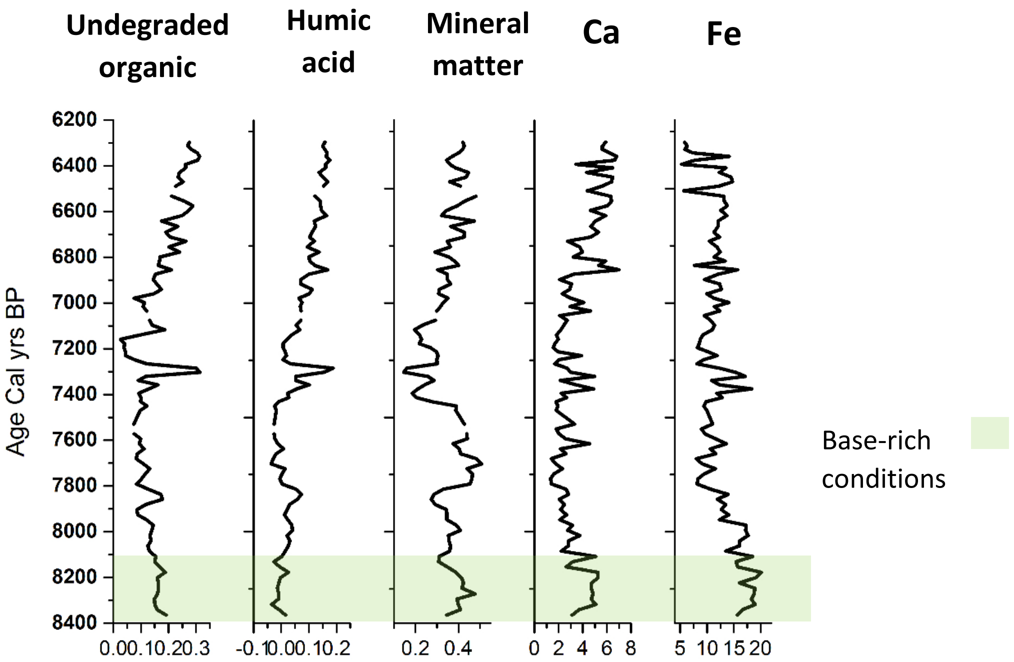


Figure 5-29: Undegraded organic matter, humic acid and mineral matte levels compared with Ca and Fe (ppm). Base-rich conditions change to bog conditions.

We can certainly see the influence of fire events on the soil chemistry at Robinsons Moss shown by the geochemistry results for the lower section of the record. Concurrent with the major fire events around 7300 years BP there is an increase in Fe (Figure 5-29). Leaching of Fe and Ca can lead to an increase in acidic conditions by reducing the base ions (Rydin & Jeglum, 2006). Invasion of *Sphagnum spp.* and *Calluna* expansion also has a positive feedback effect on this process. When present in the system they can contribute to the acidic conditions and waterlogging as the undecomposed organic remains of the *Sphagnum* increase.

The natural process of peat development could be enhanced by increased waterlogging due to the deposition of charcoal fragments (Charman *et al*, 2013), although peat development occurs with other disturbances such as deforestation. The NIRS results in figure 5-29 and figure 5.30 show that the humification level decreases and the level of undegraded organic material increases after the local fire event at 7320 – 7340 years BP indicating a raised water table. The soil changes from base-rich conditions to ombrotrophic mire conditions in a step wise transition as shown by the NIRS analysis. This is also concluded by Tallis (1991) in his study at Robinsons Moss. This is a natural process involving waterlogging and a relatively rapid change to more acidic conditions led by the growth of *Sphagnum* mosses and Ericaceous species. Any natural waterlogging would have been enhanced by the addition of charcoal fragments into the soil and could have hastened the expansion of the peat blanket.

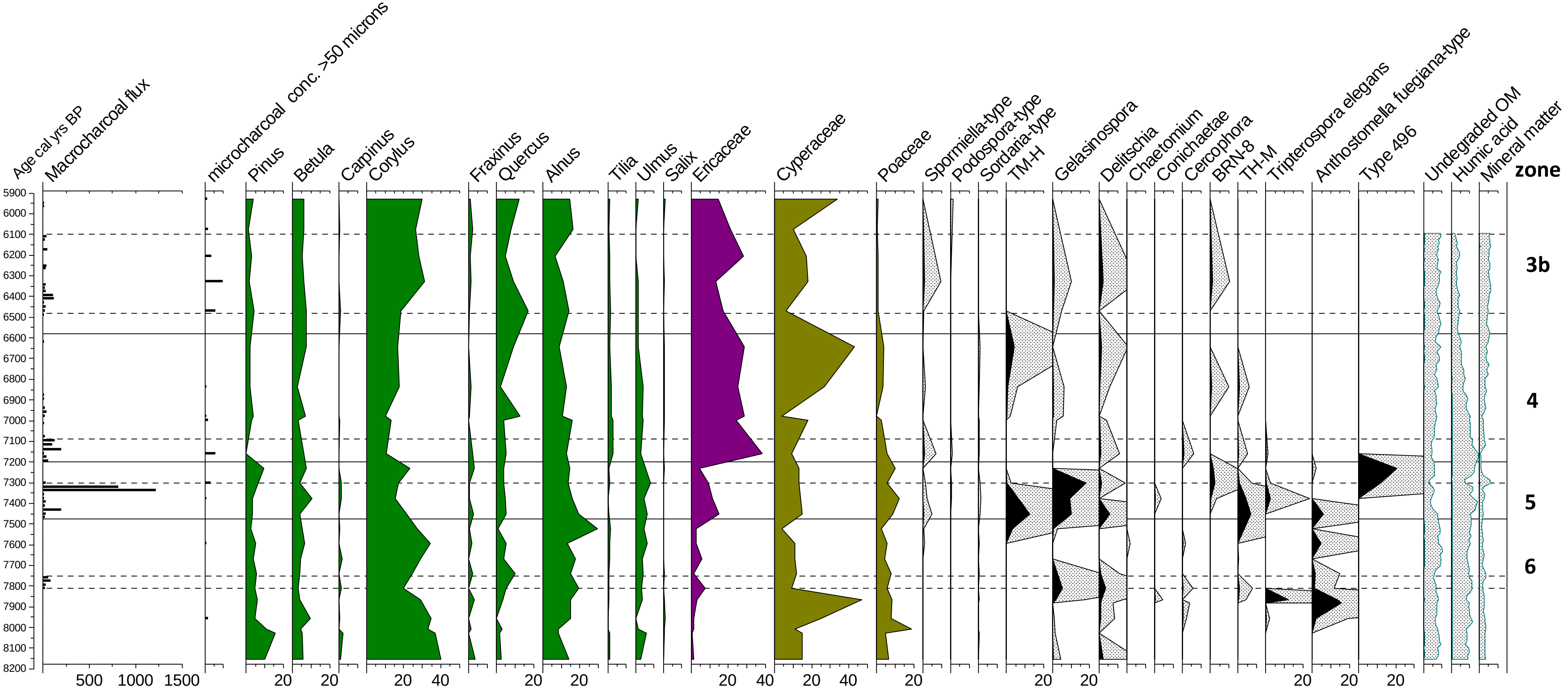


Figure 5-30: Charcoal, pollen, NPP and NIRS diagram (Grimm, 2011) showing macrocharcoal flux (area mm^3/cm^2/yr^{-1}) a selection of pollen percentages and fungal spore concentrations. The NIRS (results are shown with exaggeration x100. The fungal spore data shows exaggeration x20.

5.7 Discussion

Charcoal fragments can be described using several parameters such as abundance, area, size and shape. These parameters can then be used to explore the relationships between fire and other environmental factors such as vegetation dynamics and climatic conditions. Some of these parameters will be used to provide evidence in answer to the second research question for this thesis.

A. How (and why) has the fire regime altered during the Holocene at Robinsons Moss?

Trends in the fire regime

At Robinsons Moss, macrocharcoal influx values from 8200 years BP to the present day show distinct zones of high, medium and low values (figure 5-30). This indicates changes in biomass availability and/or changes in the ignition source. Issues taken up in this discussion include: Can the type of fuel burnt at Robinsons Moss be determined? Biomass availability is linked with vegetation succession and biofeedback mechanisms to climatic conditions. Pollen and fungal spore data can provide additional evidence for fuel biomass as they can often be interpreted to identify local flora. It is difficult to separate ignition sources, for example human activity and natural lightning strikes, but there is evidence that Mesolithic tribes were using the Peak District as a resource. There are periods of little or no fire at Robinsons Moss that are also part of the fire history.

Fire Zone 1 (6580 to around 4900 years BP)

The fire return interval (FRI) is at the lowest value at 141 years (eight fires per 1000 years), shown in table 5-5 and figure 5-25. The macrocharcoal fragments were divided into three groups determined by the W/L ratio shown in figure 5.31B. From 8200 – 5800 years BP, there is a mixture of all three size categories, however it is the peaks in the largest size (W/L ratio > 0.75), an indication of burning wood (Umbanhower & McGrath 1998), shown by brown symbols that correspond to peaks in the RDA variance curve for macrocharcoal fragments (also shown in figure 5.31B) for this section of fire zone one. From 5800 – 4000 years BP there is a greater proportion of the middle fragment size (W/L ratio is between 0.5 – 0.75 shown by purple symbols) and it is the temporal peaks in this category that correspond to the highest values in the RDA variance curve. It is likely that ericaceous shrubs are the major source of the burnt material is creating this mid- size category. Figure 5-10 shows that this period corresponds to an increase in *Meliola ellisii*; this fungal spore indicates the local presence of *Calluna vulgaris* (Van Geel et al, 2006). The pollen proportions calculated using the LOVE model (Sugita, 2007a) in figure 6-21 show the dominance of *Calluna vulgaris* from 8200 to ~ 800 years BP. *Calluna* and other heather spp. are significantly correlated with the microcharcoal record which could indicate that a portion of the microcharcoal record is recording local vegetation assemblages and that burning of *Calluna vulgaris* explains some of the fluctuations in the fire record. There is generally more burnt grass shown by the smallest charcoal fragments (green symbols) from 8000 – 5500 years BP which corresponds to peaks in Poaceae.

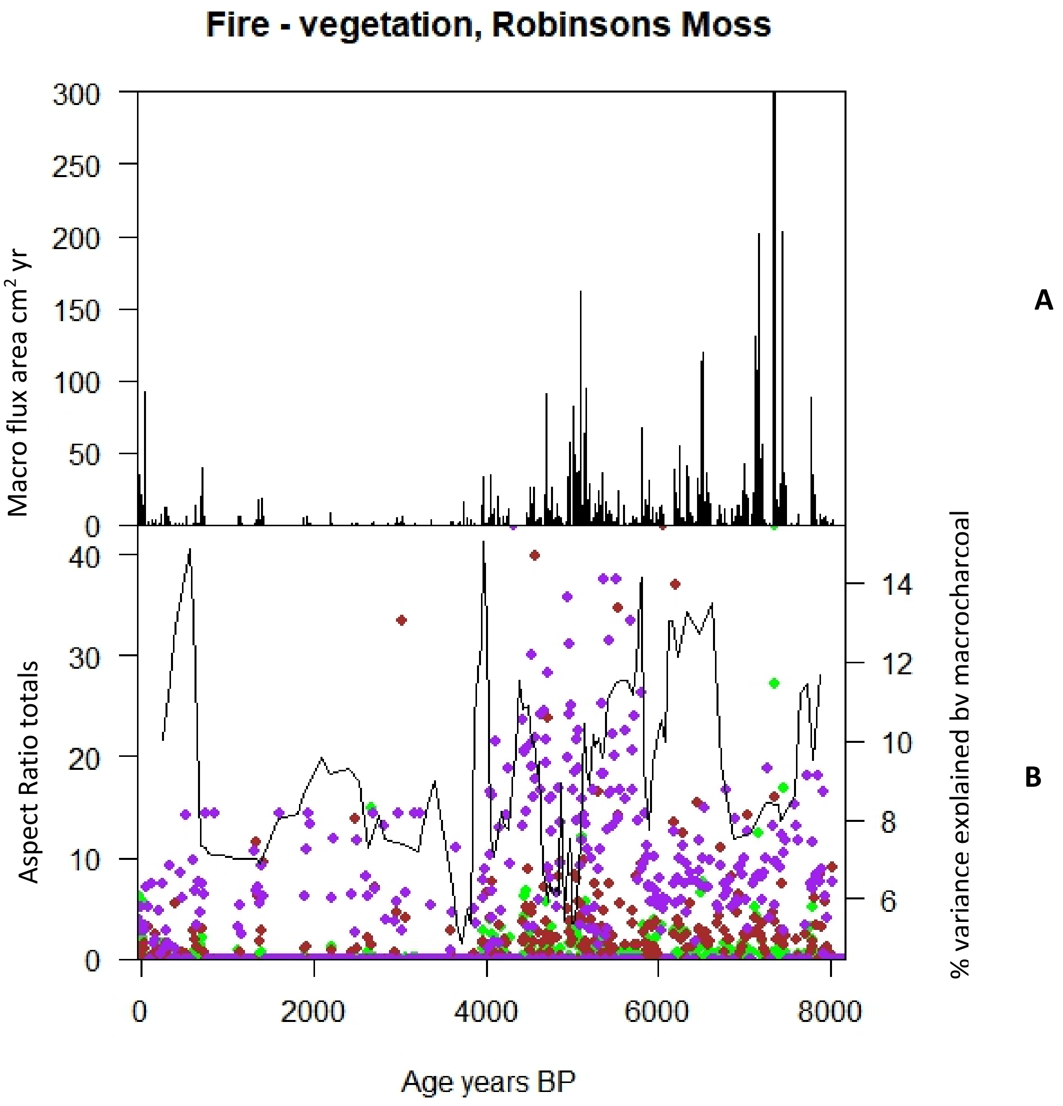


Figure 5-31: Macrocharcoal fragment influx (black bars), (A). RDA values with macrocharcoal as constrained variable (black line) with macrocharcoal fragments divided into three sizes; W/L ratio < 0.5 (green symbols), W/L ratio >0.5 < 0.75, W/L (purple symbols) and W/L ratio > 0.75 (brown symbols) (5.30 B), (B). Both graphs plotted against Age Cal years BP.

Fire Zone 2 (4900 – 2850 years BP)

The FRI increases from 4900 – 2850 years BP to 190 years FRI with a mean value of six fires every 1000 years (figure 5-25) so fires are less frequent than in the previous zone. The fragment size category (W/L > 0.75; burnt wood) reduces in peak size from 5000 to 4000 years BP. It is these larger pieces that correspond with the general trend in the reduction in fire events that could indicate the burning of tree species. It is in this zone that the highest peaks in the burnt wood size category occur. The microcharcoal record shows significant positive correlation with *Quercus,* Poaceae and Ericaceae and a negative significant correlation with *Pinus.* Hence, at this time it could be *Pinus* that is burning as well as Ericaceae, however Ericaceae gains in abundance with fire whereas *Pinus* reduces. In successional terms, *Quercus* would expand into the gaps left by *Pinus*. This category still has only a small presence in the record that is dominated by the middle size of fragments as in the zone described above. Around 4200 years BP, the macrocharcoal record (figure 5.31A) shows that fire events reduce from a medium level to a low value and continues at a low level until the last millennia. Unlike the macrocharcoal record, the microcharcoal record continues at a medium level until around 2200 years BP. The vegetation zones 3a and 3b from 6580 – 2850 years BP (figure 5-10) are complex as shown in the 3D plot of the vegetation zones (figure 5-15) where 3a and 3b are not dominated by any of the first three PCA eigenvectors. The description above could explain some of the complex dynamics seen in the Robinsons Moss record for these two vegetation zones. The burnt grass peaks generally correspond to peaks in Poaceae.

Although fire events show a contrast in value between zones 3a and 3b, there are no dramatic changes in the pollen taxa. There is an increase in *Calluna vulgaris* and an increase in the OPEN variable (figure 5.14) with fluctuating levels of *Quercus* (figure 5-10). This would indicate that the local biofuel is heather taxa and that trees are burning in the wider region surrounding Robinsons Moss. There is also indication that fire is not the dominant driver for this time period reflected in the lack of significance in the pollen taxa tested for correlation with macrocharcoal fragments shown in table 5.2.

Zone 3 (2850 to 800 years BP)

The FRI increases to 243 years with the frequency of fires per 1000 years ranges from six to two during this this period. Figure 5-31 b above shows the consistent level of mid size fragments with only a few occasions where larger and smaller fragments are found. Pollen percentages show that tree taxa, herbs and shrub taxa do not show any dramatic change (figure 5-32). A significant fire event occurs around 2500 years BP shown in the microcharcoal record, but otherwise, fire events are very minor. This fire event occurs during the Iron Age so could be explained by deforestation by people at this time. The pollen proportion diagram (figure 6-12) shows a regional increase in *Calluna vulgaris* pollen proportions and reducing proportions for local trees *Alnus, Betula* and *Corylus*, however the local diagram shows increasing *Calluna vulgaris* and reducing proportions for tree taxa. Clearly there are local differences in the sites used in the regional study shown in Chapter five. The increase in burnt grass size charcoal fragments can be seen in figure 5-31 B above around 800 years ago is at the time that sheep grazing was a major activity for upland Peak District areas (Davies *et al*, 2016).

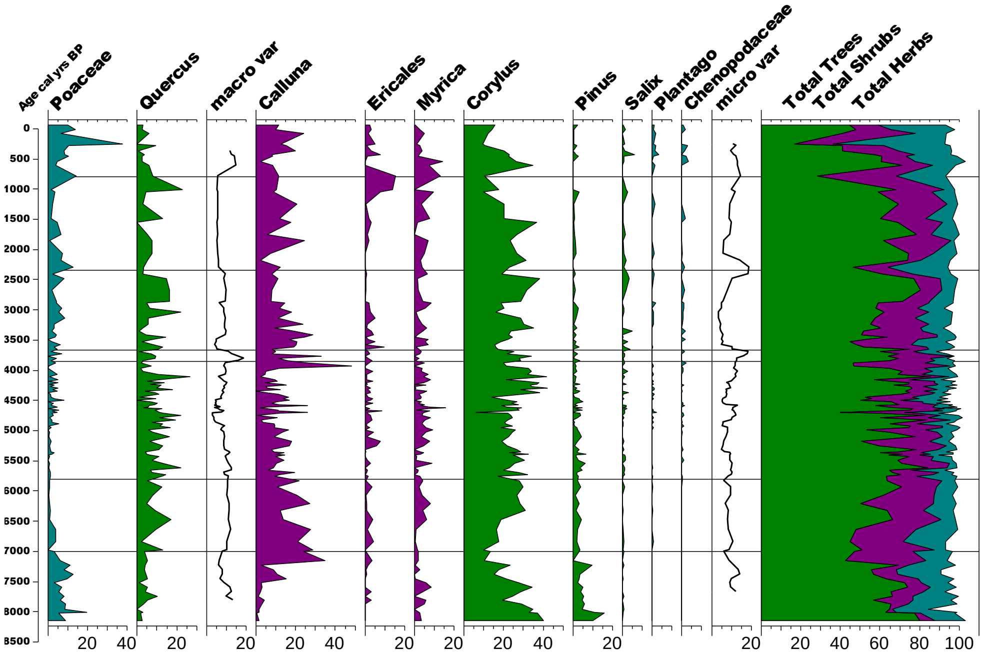


Figure 5-32: Pollen and charcoal diagram (Grimm, 2011) showing RDA percentage variance values for microcharcoal conc. and macrocharcoal flux with selected pollen taxa.

Fire frequency controls: climate, vegetation or human activity?

Peat mire systems are excellent archives of fire history. Mire systems develop and expand under specific environmental and climatic conditions (Charman *et al*, 2013; Rydin & Jeglum, 2002) hence the accompanying pollen data will include peat development history as well as regional climate signals. Defining regional shifts in climatic conditions using independent palaeoecological data is difficult as this data also includes information on ecosystem response to past climate change (Bradshaw & Sykes, 2014) which may or may not match the system being investigated depending on the location of the climate record. A compilation of climatic shifts defined using palaeoecological data is displayed as table 2-2. Interestingly, the time period showing shifts to drier climatic conditions from 6,600 years BP to 5,800 years BP corresponds to a short period where charcoal fragment flux abundance increases at Robinsons Moss from 6,500 years BP to 6100 years BP. Ice core records (Andersen, 2004) can be useful for continental wide studies but do not have the resolution to be useful for regional studies. Research indicates that climate was a dominant ecosystem driver across N. Europe from the last deglaciation to the Holocene climatic optimum (9000 – 5000 years BP) and land use change through human activity becomes increasingly important up to present day (Molinari *et al*, 2013; Froyd, 2006). Conditions favourable for fire on mire systems is a dry season with a decrease in the water table and periods with frequent fire often correspond to periods of drier climatic conditions. From 7500 – 5000 years BP frequent fires are seen in palaeoecological records across Europe and remained frequent up to 2500 years BP although the climate was generally moist and cooler after 6000 years BP (Pitkanen *et al*, 1999). So how does the fire history for Robinsons Moss compare with broad climatic trends for the U.K. and is there evidence that any of the variation in the charcoal fragment abundance was a result of human activity for the 8000 years that the record covers? Fires need suitable flammable biomass so what vegetation is burning at Robinsons Moss?

Conditions for fire to occur are dependent on several factors including the availability of suitable biomass such as flammable tree species e.g. *Pinus sylvestris.* In the previous section of this discussion, the charcoal record was described in terms of correlation of the charcoal fragments with various tree taxa. There is certainly evidence of forest cover for the Peak District region. Tallis (1983) found *Salix* remains at Robinsons Moss and *Betula* remains at nearby Featherbed Moss dated to 7675 ±65 and 7550 ± 60 respectively. Tallis (1983) also found rooted stumps both in and beneath peat at various sites in the Peak District providing evidence of a former forest in this area. Table 3 on page 595 in Tallis (1983) shows the extent of tree roots found in or below the peat. Tallis concluded that the trees represented the fossilised relics of the former forest before the mineral soil was overlain with a blanket of peat (Tallis, 1983). The palynology presented in this chapter confirms the continuation of tree taxa at Robinsons Moss until around 800 years BP. Tree taxa such as *Pinus* are likely to provide fuel in fire events. Caseldine & Maguire (1986), Tallis (1990) and Charman *et al* (2000) and all show disturbances in U.K. upland forest. Forest recession can be seen in the pollen diagrams at Waun-Fignen-Felen, S. Wales ((Cloutman & Smith, 1988). The early forest at Robinsons Moss would be growing in shallow peat. Reduction in the forest could open up niche areas, for example; areas of bracken, heather and grass species on drier ground and sedge, rushes and herb species in wetter areas. Open areas with a high water table would encourage the expansion of *Sphagnum* or *Eriophorum* species. These different areas could expand and contract during shifts to wetter or drier climatic conditions.

Significant fire events have been identified for Robinsons Moss by using both the CharAnalysis programme (Kelly *et al*, 2011) and the analysis completed using ARCO (Finsinger, 2014). These occur at ~ 7800, ~ 5000, ~ 4000 and ~ 800 years BP. There is some correspondence of the timing of these fire events with human activity during the Mesolithic, expansion of agriculture, Bronze and Iron Age, so some of the intense fire periods could be the result of deforestation during these periods, but it is difficult to be certain. A pattern of repeated disturbance and regeneration is seen in the North York Moors during the mid Holocene (Innes *et al*, 2010). Innes indicated that fire was responsible for this pattern and that fire events did not correlate with wet/dry shifts in the climate. There is ongoing debate regarding the impact of early anthropogenic activity at upland sites such as Robinsons Moss. Research such as Simmons *et al* (1981), Cayless & Tipping (2002), Gallego-Sala *et al* (2015) in the U.K. and Marlon *et al* (2008) in research on global fire favour the predominance of climate driven fire events, whereas Mackay & Tipping (1994), Dark (2000), Fyfe *et al* (2003), Froyd (2008) are all studies that discuss human activity as a driving factor for fire events. Complication in the interpretation of pollen and charcoal records arises as human activity during early and mid-Holocene was influenced to a greater extent by climatic conditions than it was during late Holocene up to present day.

Drier, warmer climatic conditions would encourage expansion in tree taxa to higher altitudes than under colder climatic conditions and could make these higher altitude areas more amenable for people. Coprophilous fungi have provided evidence for dung left by grazing animals at this site during a 350 year time period from 7450 to 7100 years BP. The transition zone between tree taxa and shrub taxa would have been an attractive habitat for grazing animals such as Red Deer (*Cervus elaphus*) feeding on the resources available in the open areas. Archaeological evidence for Mesolithic people has been found in the Peak District. Preston *et al* (2012) states that the Central Pennines is the most concentrated area of Britain for Mesolithic settlements. Other studies also find that early tribes within the

Peak District used this area to expand their hunting grounds at the forest edge (Jacobi, 1976, Spikins, 1999).

The significant fire events listed above occur at 400, 200, 300 and 400 years respectively after synchronous European changes in tree taxa found by Giesecke *et al* (2011) at 8200, 4800, 3700 and 1200 years BP so if this represents a lag after the European change, the fire events could be climatically driven by increases in the biofuel load. Table 2-2 shows the selected climate records for the U.K. indicating that between 6600 and 5800 years BP conditions were drier. This period corresponds to a zone in the RDA response data where fire (macrocharcoal fragments) explained around 13 % of the vegetation dynamics at a relatively constant level during this 800 year period. This shows a synchronicity of climatic conditions impacting on the fire regime through the vegetation dynamics.

Corylus percentage reduces from 24.5% at the time of high fire (~7775 years BP) to 10.3% ~7158 years BP, 600 years later whilst other tree taxa do not exhibit such a change in percentage, so whilst it is possible that people are manipulating the vegetation at Robinsons Moss during this shorter time period it is probable that the more extensive reduction in *Corylus* that occurred at Robinsons Moss from the basal layer (8200 years BP) to around 5400 years BP is in line with the synchronous changes in tree taxa explored by Giesecke *et al* (2011). Giesecke showed that the times of change for *Corylus* and *Alnus* was synchronous across Europe which could only be a climatically driven change and states that this change could be the result of a climatic trigger that occurred 500 – 1000 years earlier.

Fire events can be also be discussed in relation to the fungal spore assemblage. The fungal spore assemblage changed following a major local fire event at ~ 7100 years BP with the absence of fungal spores indicating rotting local trees after this time (figure 5-30). The fungal spore assemblage has also indicated shifts in the hydrology at Robinsons Moss. Two fungal spores have been recorded that indicate temporary water, Spermatophore of *Canthocampus* and *Cladocera* remains. *Cladocera* remains are significantly correlated with the macrocharcoal record (*Canthocampus* is not) and neither correlate with the microcharcoal record, although *Canthocampus* corresponds to a period of reduced fire from 6500 – 5500 years BP. The presence of these arthropods indicates temporary water (Van Geel, 1976, 1983, 1988).

5.8 Conclusions

The palaeoecological data presented in this chapter is one of the longest records available for the U.K. and as such provides an environmental history covering 8200 years. Adolf *et al* (2017) concluded that high resolution pollen and charcoal records can provide crucial information for future ecosystem response to increasing fire hazard under changing global conditions.

The CharAnalysis results showed that the FRI varied during this long record. The results from the correlation analysis shows that flammable tree taxa such as *Pinus* and shrub taxa dominated by *Calluna vulgaris*, were probably the vegetation that was burning at different times throughout the ecological history of Robinsons Moss as these taxa are both correlated with the fire record. Human activity during the Mesolithic and during other times of population expansion correlate with significant peaks calculated using CharAnalysis and confirmed with the ARCO programme. However, separating human activity from climate change is difficult as these ecosystem drivers were more intertwined during the early and middle Holocene than during the late Holocene.

Although there are differences in the fire history provided by the microcharcoal and macrocharcoal fragments. These records represent a similar impact on the vegetation dynamics except for the major local fire that occurred around 7200 Years BP as shown in figure 5.16. For this fire event, macrocharcoal flux record shows a higher impact on the vegetation dynamics.

The overarching evidence in this record suggests that although fire events impact on the local vegetation and soil geochemistry, climate is probably the dominant driver of vegetation dynamics during the Holocene from 8200 – 2000 years BP at Robinsons Moss.

Chapter 6 Holocene fire-vegetation dynamics in the Peak District

6.1 Abstract

Two major peat fires occurred in northern England during the summer of 2018 highlighting the devastation that wild fires can have on peat ecosystems. Prescribed burning continues to be a challenged and debated issue for these ecosystems (Marrs *et al*, 2018). Paleoecology can contribute evidence concerning the long-term impact of fire on peat ecosystems and their role in vegetation dynamics. Summer temperatures are forecast to rise over the next 50 years, which could increase the probability of wildfires in these landscapes. To explore the role of fire during the Holocene at upland moorland sites in and around the Peak District, this study used several middle/late Holocene fire records with local and regional pollen proportions for key taxa. Here we calculate quantitative values for the level of impact on the vegetation dynamics explained by fire events using redundancy analysis. Results show the maximum percentage explained by fire is 26% across the Peak District, with the implication that climate is the major driver for middle to late Holocene upland peat areas. However, the temporal and spatial heterogeneity shown by the local pollen proportions at the different sites indicates local disturbance regimes and local environmental conditions for peat expansion.

The philosophical study of nature endeavours, in the vicissitudes of phenomena, to connect the present with the past."

*— **Alexander Humboldt***

6.2 Introduction

Fire occurs when available biomass burns. As this is more likely to occur during dry conditions, climatic conditions can have a major impact on fire prone ecosystems. Two recent major peat fires in northern England in 2018 highlighted the risk of increased fire events in a warming climate (IPPC Report, 2018; https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf). This has increased the importance of investigating the long-term response of peat ecosystems to historic fire events.

There is still debate concerning the impact of early people on the Holocene vegetation in the U.K. An interesting way to explore this is through the change in forest cover for Europe as shown in figure 6-1. Here, 50% forest reduction mostly occurred pre 5500 years BP over the U.K. in contrast to Eastern Europe where this occurred much later post 2500 years BP.

The increase in archaeological sites after 6000 years BP across northern England was explored at Walton Moss by Woodbridge *et al* (2014) shown in figure 6-2 and can be used to imply the general rise in human population and increased impact on the environment such as forest cover from this time. A general reduction in woodland can be seen as peaks and troughs from 7800 to 5500 years BP in the semi-open graph in figure 6-2. Significant decrease in woodland cover in the Scottish record occurred between 5800 and 5400 years BP (Woodbridge *et al*, 2014). Forests then show a period of recovery until the greatest reduction in forest cover during the last 2000 years with a concurrent increase in archaeological sites.

Woodbridge *et al* (2014) suggested that there is a relationship between climate change, late Mesolithic populations and forest cover especially 7700 – 7600 years BP and that this would merit further study.

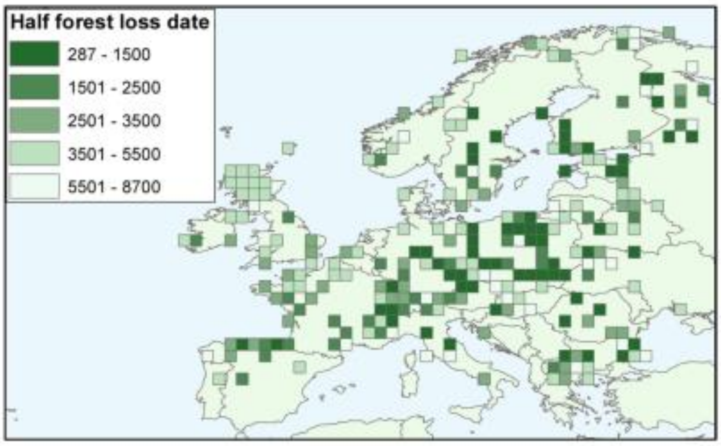


Figure 6-1: From Roberts *et al,* 2018: Europe's lost forest: A pollen based synthesis for the last 11,000years (www.nature.com/scientificreports) showing different time periods where half of the highest forest percentage cover calculated for the Holocene is reduced by 50%.

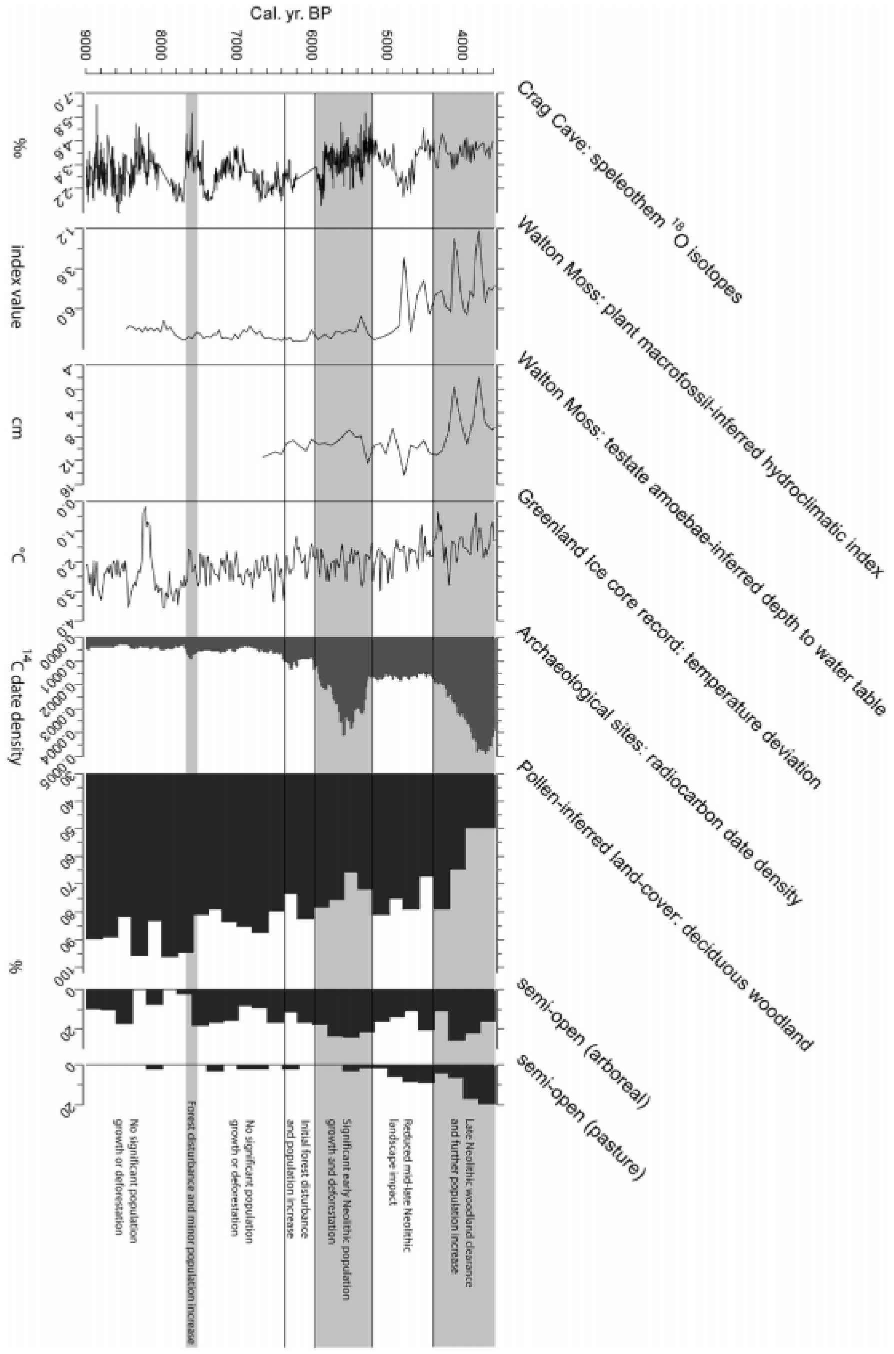


Figure 6-2: Paleoclimate records; Crag Cave (McDermott *et al*, 2001), Walton Moss (Mauquay *et al,* 2001) and the Greenland ice core record (Vinther, 2009) with an annual record of ^{14}C date distributions from archaeological sites and pollen-inferred-land-cover change (200 year time slices) between 9000 and 3600 Cal years BP. Zones relate to transitional periods identified in the pollen and archaeological records. Shaded areas illustrate periods of major increases in population levels. From Woodbridge et al, 2014.

6.2.1 Climate

Climatic conditions are intrinsically linked to upland peat environments through precipitation and the hydrology of the peat. There are few long-term records for the Peak District area. This study uses raw data from published records combined with a new 8200 year record for Robinsons Moss, an ombrotrophic bog at 500 m a.s.l. to examine the complex system of fire events, vegetation dynamics and changes in climatic conditions that have occurred across the moorland regions of the Peak District, U.K.

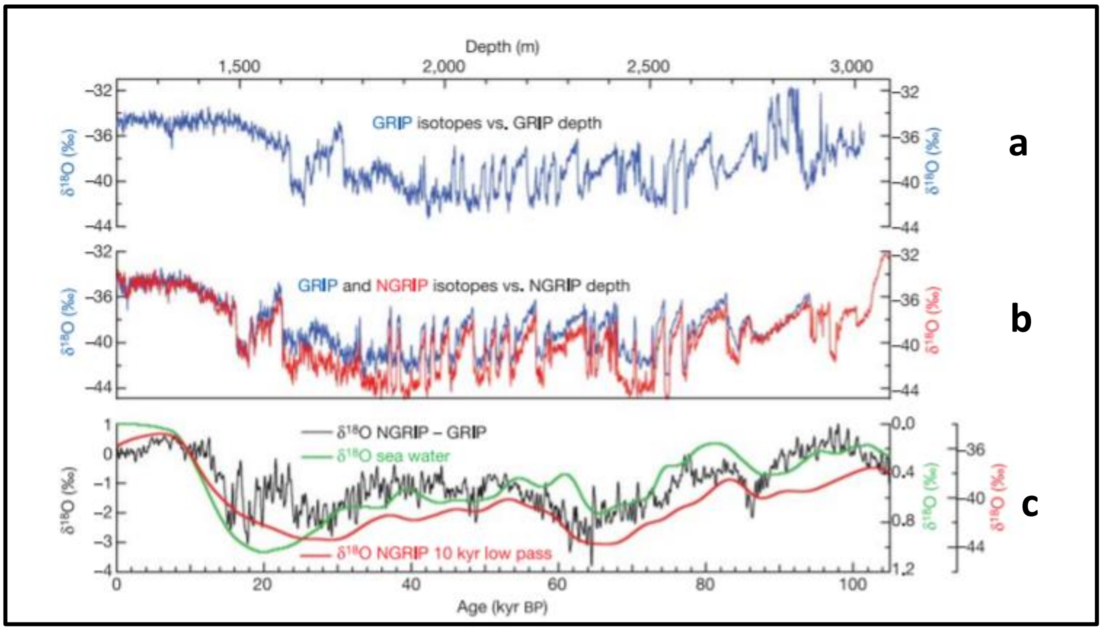


Figure 6-3: From Andersen et al (2004) showing isotopic record as proxy for temperature over the Holocene and part of Eemian period. The NGRIP stable oxygen isotopic record compared to the GRIP record. The GRIP oxygen isotopic profile (blue) with respect to depth at GRIP, a. The NGRIP oxygen isotopic profile (red) with respect to depth at NGRIP. For comparison, the GRIP record (blue) has been plotted on the NGRIP depth scale using the rapid transitions as tie points, b. The difference between the NGRIP and GRIP oxygen isotopic profiles plotted above on the GRIP2001/ss09sea timescale15 in 50 yr resolution (black). The record is compared to a record representing sea level changes39 (green) and a 10-kyr smoothed oxygen isotope profile from NGRIP (red), c. (Anderson, 2004).

General Circulation Models (GCM) using ice core (figure 6-3) or speleothem datasets (figure 6-2) can provide information about major climatic shifts for hemispherical or continental regions (Zhang *et al*, 2018) and these can be used to understand countrywide and continental shifts in vegetation dynamics depending on the scale of the compiled datasets. See figures 6-3. However, their resolution is less appropriate for understanding regional or local changes in vegetation dynamics during the Holocene. In terms of Holocene climate for northern England, there are only a few records that have reconstructed paleoclimatic conditions (temperature, precipitation) older than ~ 6000 years BP. These include Fyfe *et al* (2012), Langdon *et al* (2004), Chambers & Blackford, (2001), Hughes *et al*, (2000) and Anderson *et al* (1998). The lack of data is due in part to the limited number of sites with deep peat or lacustrine sediments. Langdon *et al* (2004) used chironomid remains for their reconstructions (figure 2-8) and Barber *et al* (2013) compared lacustrine and chironomid inferred temperature data. Other studies have used macrofossils, tephra and bog surface wetness (Mauquoy *et al*, 2002; Blundell *et al*, 2005; Amesbury *et al*, 2013; Barber *et al,* 2013). Hughes *et al*, (2000) constructed their 10,500 years BP paleoclimate record for Walton Moss, Cumbria using plant macrofossil data. Tipping and Milburn's (2000) study in Scotland, found regional wet and dry phases. Charman *et al* (2006) compiled a hydrology record for Northern Britain using testate amoebae data and also found several major wet/dry shifts at 3600, 2760 and 1600 and further minor wet shifts at 3060, 2050,1260, 860 550 and 260. These data suggest various wet/dry shifts during the middle/late Holocene (see table 2-2), although there is poor temporal correlation. Schulting *et al,* (2010) in his review of several datasets using botanical proxies suggests that a shift to drier, more continental conditions occurs ~6000 – 5800 years BP. Paleoclimate records are available, such as those listed in table 6-1, although to date, a comprehensive regional record for the last 10,000 years BP for northern England has yet to be produced. Some similar climatic deteriorations have been detected in different studies using various techniques such as wiggle matching and some climatic records listed above have been compared with records from other countries such as Germany, Denmark and Sweden with some similarity in trends identified across this wider scale.

Reference	**location**	**Age Range (cal yrs BP)**
Barber *et al* (1981)	Scotland	0 – 6000
Lomas-Clarke *et al* (2004)	Abbeyknockmoy, Galway	0 – 2045
Hughes *et al* (2000)	Walton Moss, N Britain	100 – 8000
Langdon *et al* (2004)	Talkin Tarn, Cumbria	0 – 6000
Anderson *et al* (1998)	N Scotland	0 – 90000

Table 6-1: Published paleoclimate records illustrating the variable temporal scale of paleoclimate records for northern Britain and Scotland.

Therefore, the unifying evidence from these studies suggests that there were wet/dry shifts during the Holocene across Northern Britain since at least 9,000 years BP. The impact of shifting climatic conditions on Robinsons Moss over the last 8200 years in relation to the fire regime will be explored in this chapter.

The recent history of upland U.K. peat habitats shows these landscapes to be cultural landscapes; open treeless *Calluna*-dominated with often deep peat. Albeit the Peak District is a widely studied area, there is a paucity of long-term local studies that explore the fire, vegetation dynamics and climate conditions during the early/middle Holocene. The presence of peat in the Peak District is due to its location in a restricted specific global climatic zone in which peat is able to accumulate, where water retention exceeds water loss under low nutrient, acidic conditions. Peat is a rare global ecosystem covering ~ 6% of the U.K. These peat moorlands are a significant part of global carbon sink environments (Allen *et al*, 2013) as an efficient carbon sequestration mechanism for atmospheric CO_2 (Power *et al*, 2010; Mathijssen *et al*, 2016; Garnett *et al*, 2000; Marrs *et al*, 2018). Burning this organic biomass releases carbon back into the atmosphere as gasses notably CO_2, CH_4 and as charcoal fragments. Fire events occurred in several peat environments in the U.K. during the summer of 2018 notably in the north of England at Saddleworth Moor and Winter Hill. These fires are thought to be due to a combination of factors; unusually high summer temperatures, high amounts of flammable biomass and probable human ignition. Summer temperatures are forecast to increase (Jenkins *et al*, 2009) leading to drier conditions and a likely increase in wildfires.

Fire is a current and historic management strategy for *Calluna*-dominated moorland in the Peak District. Current concerns in the management of peat habitats is how to balance expectations for maintaining biodiversity with resource management and the concerns regarding any increase to summer temperatures combined with biomass increase and the increased probability of wildfires. This is where information from paleo studies can develop our understanding of long-term ecological dynamics and the impact of early disturbance events (Conedera *et al*, 2009; Whitlock *et al*, 2012). As fire events are part of a complex network of positive and negative feedback mechanisms in vegetation and climatic systems, both long term and short term, it is only through paleoenvironmental studies that we can investigate the long-term influence that fire has on vegetation dynamics, peat development and carbon sequestration.

Robinsons Moss, one of the upland ombrotrophic peat bog sites used in this study is thought to have undergone initial paludification around 9000 Cal years BP (Tallis, 1987, 1991). During the subsequent millennia there is substantial evidence for the presence of Mesolithic tribes in this region of the U.K. (Jacobi, 1976, Spikins, 1999, Tallis, 1983, 1991; Preston *et al*, 2018) and this study shows evidence for herbivore grazing through the presence of dung fungi. This is a common theme throughout the U.K. for peat ecosystems such as North York Moors and Dartmoor in England and other peat environments in Scotland, Wales and N. Ireland. Earlier pre-industrial era evidence for the impact of early human tribes on U.K. moorlands is less clear (Fyfe *et al*, 2018). Several studies that investigate human impact on U.K. Holocene woodlands in middle to late Holocene (Innes & Simmons, 2000; Blackford *et al*, 2006a, 2006b; Tinner *et al*, 2006; Fyfe *et al*, 2018) have generally found that where humans and/or fire events are present, these drivers have a low level impact creating a diverse mosaic of vegetation assemblages. Other papers (Innes & Blackford, 2003; Tipping *et al*, 1995a, b) have questioned the assumption that human activity was the main factor in creating open spaces within woodlands. At a more local scale, obviously, there are differences in the time and level of impact due to geomorphology and other factors such as altitude and local vegetation dynamics.

The impact of fire events during the Mesolithic/Neolithic transition in the U.K. has been investigated in several ombrotrophic bogs at varying resolution over different time periods (Innes *et al*, 2010, 2004; Mighall *et al*, 2008; Blackford *et al*, 2006; Tallis, 1991). The research found repeated patterns of disturbance and regeneration of woodland species and charcoal fragments in many samples. Fyfe *et al* (2018) in this study of Dartmoor, where peat also developed prior to 6000 years BP, similar to Robinsons Moss, highlighted the complex history of peat environments in the U.K. Fire is a common factor in these peat ecosystems, but how much of the fire regime is natural, how much was ignited by humans and the impact that fire has on these habitats is still poorly understood. Across the U.K., disturbance, events increased once human activity and land change activity took a much firmer hold on the environment during the Bronze Age and then continued through the Iron Age and Roman invasion. Environmental history over the last 200 years for *Calluna*-dominated moorland in the Peak District, U.K. has been one of intensive management including prescribed fire to provide food for sheep (*Ovis aries*.L) and red grouse, *Lagopus lagopus scoticus* (Lathom) and tree removal (Allen *et al*, 2013; Davies *et al*, 2016). In a wider context across N. Europe, work such as those in Finland (Mathijssen *et al*, 2017; Morris *et al*, 2015; Pitkanen (1999), Russia (Kuosmanen *et al*, 2014), Sweden (Hannon *et al*, 2018;

Molinari *et al*, 2013; Olhson *et al*, 2006, 2013) and Ireland (Hawthorne *et al*, 2016; Stracher, 2018; Swindles *et al*, 2010; Mighall *et al*, 2008) also investigated the impact of human activity and climatic conditions on the natural fire cycle.

These studies highlight that the interactions between major ecosystem drivers make analysis difficult. A further factor that needs to be understood in order to untangle the effect of episodic events (fire events, human activity, changes in climatic conditions) is the development and growth of peat. This requires an understanding of the hydrology of the ecosystem in question and subsequent links to climatic conditions. A peat bog often goes through a transition stage from a base-rich system to a bog system. Once a bog has progressed from being minerogenic to ombrotrophic and the two distinct layers, the anaerobic acrotelm and the aerobic catotelm have developed, then a link between precipitation and temperature can more easily be related to the vegetation dynamics and hence climatic conditions. This link can be inferred from multiproxy datasets such as palynology, plant macrofossil, insect (Coleoptera), testate amoebae, geochemistry and charcoal analysis. NPPs as well as changes in humification levels can also be used to infer ecological conditions.

6.2.2 Holocene U.K. vegetation trends in peat ecosystems

Using the LRA algorithm (Higuera, 2007a, 2007 b) local and regional pollen proportions for key taxa can be calculated. This is based on weighting the raw pollen values with pollen productivity estimates to reveal a more accurate reflection of the changing values of key species. This can assist in looking at the degree of openness in landscapes.

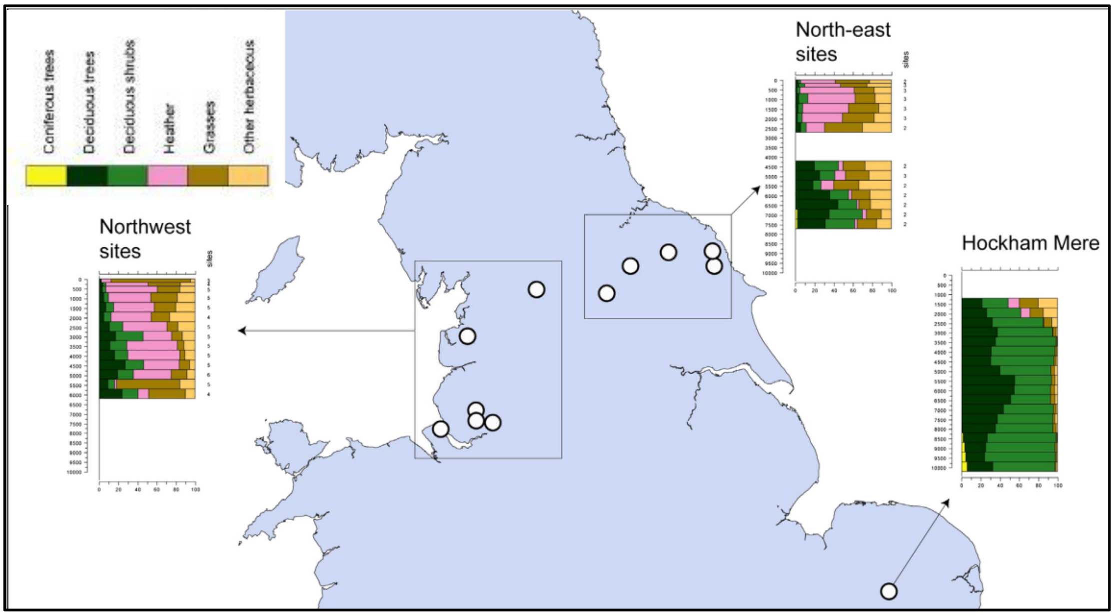


Figure 6-4: From Fyfe *et al*, (2013) showing landscape adjusted pollen percentage estimates (Sugita, 2007a) of coniferous and deciduous trees, deciduous shrubs, grasses and other herbaceous taxa for Northwest, North-east areas of England and also Hockham Mere, England. Shrub taxa show higher values using this method compared with pollen percentages.

A recent study by Fyfe *et al* (2013) used the LRA devised by Sugita (2007a, 2007b) to calculate adjusted local pollen proportion estimates for groups of sites across England. This study found that mid Holocene landscapes on Exmoor were spatially heterogenic and that this would not be evident using pollen percentage data (Fyfe *et al*, 2018). Fyfe *et al* (2013) used the LRA algorithm to explore the Holocene landscape openness across England; he looked at six sites in the Northwest and five sites in the Northeast region. The composite diagram for the Northwest in figure 6-4 shows a high proportion of shrubs post- 5000 years BP and a reducing proportion of tree taxa. Using pollen proportions, a more realistic emphasis is given to low pollen producers. The study by Fyfe looks at a range of northern sites at various altitudes across a west to east trajectory (figure 6-4). This study will look at sites above 240 m a.s.l. from 60^{0} 1” 000’ N to 36^{0} 8” 800’ N to reconstruct local vegetation proportions in and around the Peak District.

Similar to other moorland ecosystems in the U.K. such as Dartmoor and North York Moors, The Peak District has a long history of fire events and human activity. Calculating the local pollen proportions could highlight the local impacts of disturbances such as Mesolithic activity on the local vegetation (Griffiths, 2017; Albert *et al*, 2015; Innes *et al*, 2013; Blackford *et al*, 2006). Here, we focus on sites from the north to the south of the Peak

District using the LRA programme to calculate local pollen proportions and regional pollen proportions (Sugita, 2007 a, 2007b). The separation of the regional pollen signal from the local pollen element is an important issue in developing our understanding of the development of peat sequences and the immediate and long-term local impact of fire events on these ecosystems. The original pollen percentages are then analysed using redundancy analysis (RDA) to calculate the percentage of variance in the vegetation dynamics that is explained by charcoal fragments as a proxy for fire events.

6.3 Study areas and sites

The Peak District is a complex landscape of vegetation types over low and higher altitudes that include peat bogs, heather, woodland, grassland and reservoirs. It covers around 300 Km^2 of the southern Peak District (Tallis, 1985) and can be divided into two main areas relating to the underlying geology. The White Peak lies on a Carboniferous Limestone plateau (300 – 450 m a.s.l) and the Dark Peak generally lies on Millstone grit. The highest elevation is Kinder Scout at 636m a.s.l. A brief vegetation history of the Peak District can be found in chapter five. The study sites in NW England are shown in figure 6-5. Figure 6-5a indicates the position of Robinsons Moss within the Peak District.

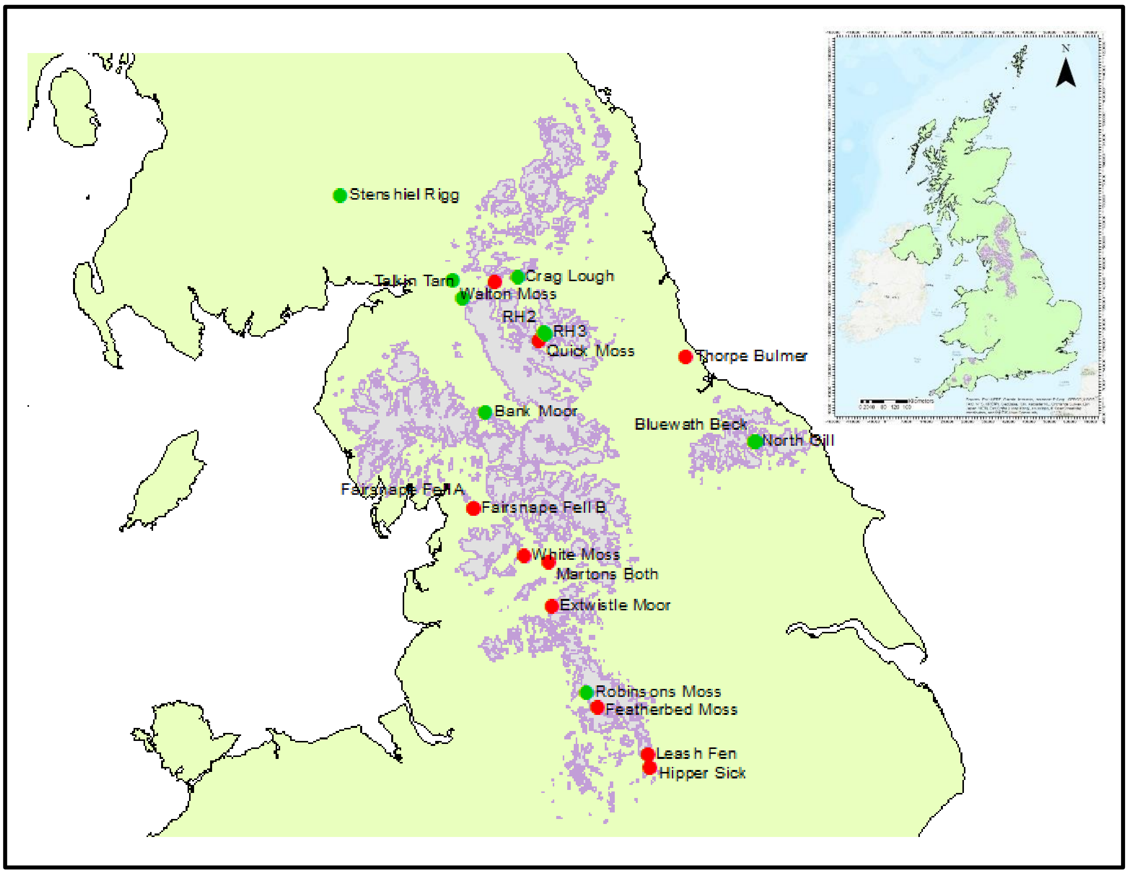


Figure 6-5: Map showing all sites considered for analysis. Purple area defines land above 200 m a.s.l. Sites included in various analyses shown by green dots and rejected sites shown by red dots.

6.4 Materials and methods

6.4.1 Fieldwork

Fieldwork for Robinsons Moss was conducted in 2009. All methods for Robinsons Moss are described in chapter five and the details for the other sites can be found in the papers listed in table 6-2.

Site name	Easting	Northing	Elevation m a.s.l.	Code	Author	Age years BP	Site type
Robinsons Moss	5348220	1941878	500	RM	unpublished	0 - 8200	Blanket peat
Bluewath Beck	473500	500800	250	BB	Innes *et al* 2010	4848 - 7000	Basin peat
Crag Lough	376600	568000	250	CL	Dark 2005	-55 - 5000	lake
RH3	387700	545400	535	RH3	Mighall *et al* 2004	-10 - 1600	Blanket peat
Stansheil Rigg	305000	601000	240	SR	Cayless & Tipping 2002	-50 - 8500	Peat basin
Talkin Tarn	0242380	5455190	130	TT	Langdon 2004	0 - 6000	Kettle hole lake

Table 6-2: Meta information for sites used in fire-vegetation dynamic analysis for the Peak District.

6.4.2 *Methods*

Methodologies used for the Robinsons Moss record can be found in Chapter five and methodologies for the remaining sites can be found in the relevant papers shown in table 6-2.

6.4.3 Age depth model

Age-Depth model for Robinsons Moss can be seen in Chapter five. The four calibrated ages were calculated using Bacon package in R (Blauuw and Christen, 2011) used to reconstruct Bayesian accumulation histories through combining radiocarbon and other dates with prior information and confirmed with CLAM in R (Blauuw, 2010).

The radiocarbon dates for all other sites were taken from the published datasets with permission from the authors or downloaded from the European Pollen Database (http://www.europeanpollendatabase.net).

6.4.4 Statistical analysis

To investigate the relationship between past fire events and vegetation dynamics, the LRA algorithm (Sugita, 2007a, 2007b) was employed so that local pollen proportions could be used to compare with the macrocharcoal flux values. To determine the response of the vegetation assemblage to fire events, RDA values were calculated using a 10 point moving window using the VEGAN package in R (Oksanen, 2018).

Quantitative vegetation reconstruction

Regional and local pollen proportion estimates were calculated for upland peat at sites within and surrounding the Peak District using LOVE and REVEALS Landscape Reconstruction Algorithm (Sugita, 2007a, 2007b). The LRA is a two-step model-based correlation algorithm than can be applied to pollen count data to estimate vegetation abundance (Fyfe *et al*, 2018). The first step involves applying the REVEALS model (Sugita, 2007a) to estimate regional vegetation composition using pollen percentages from several small sites in combination with species-specific pollen productivity and dispersal values. The LOVE model (Sugita,2007b) uses the regional pollen proportion estimates derived from the REVEALS model with pollen productivity and dispersal values to estimate the distance weighted proportion of a selection of pollen taxa within the source area of the target site (Sugita, 2007b). Local estimates were derived from regional estimates that did not include the target site (Fyfe *et al*, 2018). The bog model was used for all sites except Stansheil Rigg for which the lake model was used (Sugita, 1993). Pollen productivity estimates and pollen fall speeds were obtained from Broström *et al (2008)*. pollen percentages were converted into 500 year bins to enable comparison between sites.

LOVE pollen proportion estimates were calculated using LOVE V4.6.1 (Sugita,2007a) for several sites. This allows for a more realistic regional review as local conditions vary across regions (Fyfe *et al*, 2018). The pollen source area was set to 400 m and increased at 10 m increments. The default wind speed of 3 m.s^{-1} was used. The estimated local pollen source distances were calculated at 10m increments until the estimates of all pollen source areas were $\geq$ 0 within 1 S.E. of the estimates for the regional pollen source distance. The pollen records used for the REVEALS and LOVE models are from sites above 240 m a.s.l.

Redundancy Analysis

Charcoal data were available for five sites of the seven sites as in figure 6-5 above. Redundancy analysis (RDA) was completed using each of the micro charcoal records and the respective pollen percentages records for each site shown in table 6-2. Charcoal fragment values were used as the 1st constrained variable. The percentage of variance in the vegetation dynamics explained by charcoal was calculated using a 10 sample moving window.

6.5 Results

The sites used for calculating regional pollen proportions show very different proportions for the pollen proportion sums of trees, shrubs and herb taxa. There are clear local differences in the pollen proportions for the sites. The differences in the temporal range for the sites means that they are difficult to compare on an individual basis. Regionally, *Calluna vulgaris* expands around 5000 years BP. This occurs at least 3000 years earlier at Robinsons Moss. The local pollen proportions calculated using the LOVE programme (Sugita, 2007a) show that visually, the macrocharcoal corresponds with changes in the *Calluna vulgaris* proportions.

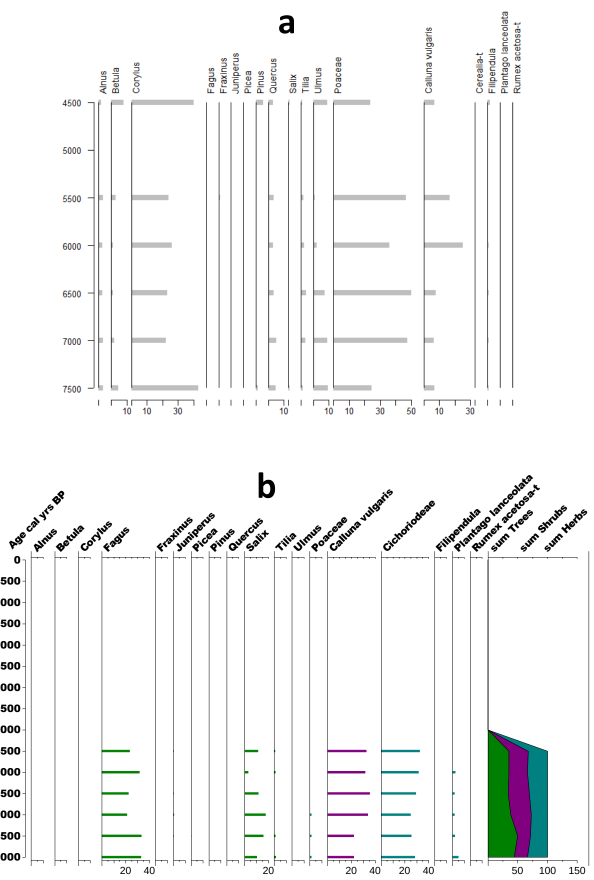


Figure 6-8: Bluewath Beck (Innes *et al,* 2010) a) Regional and b) local pollen proportions for a selection of taxa.

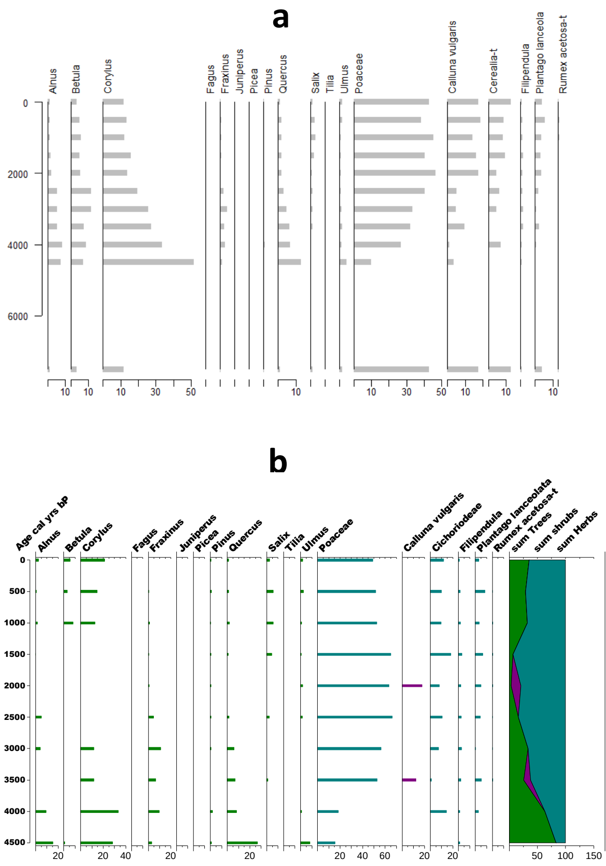


Figure 6-7: Crag Lough (Dark, 2005) a) Regional and b) Local pollen proportions for a selection of taxa.

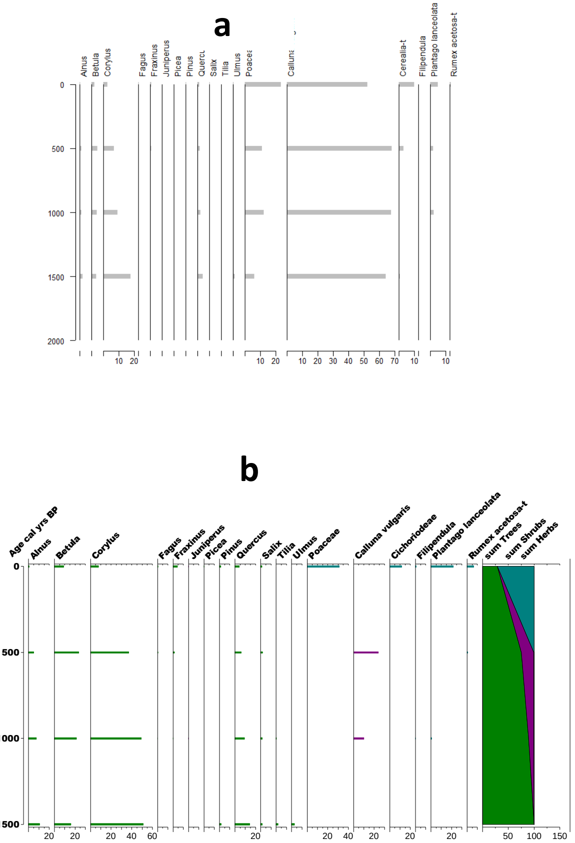


Figure 6-6: RH2 (Mighall, 2004) a) Regional and b) local pollen proportions. *for a selection of taxa.*

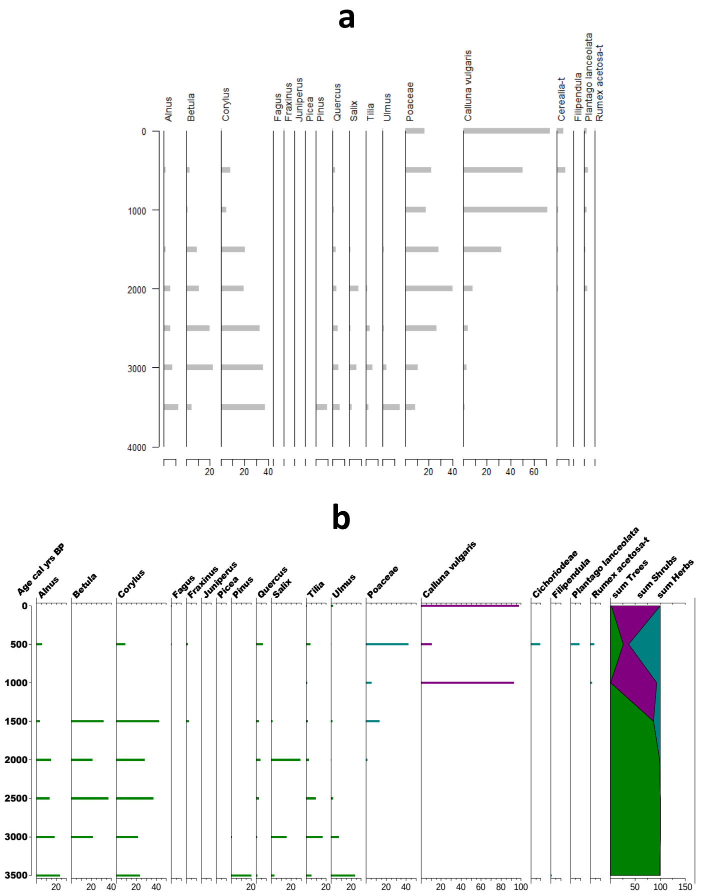


Figure 6-10: RH2 (Mighall, 2004) a) Regional and b) local pollen proportions for a selection of taxa

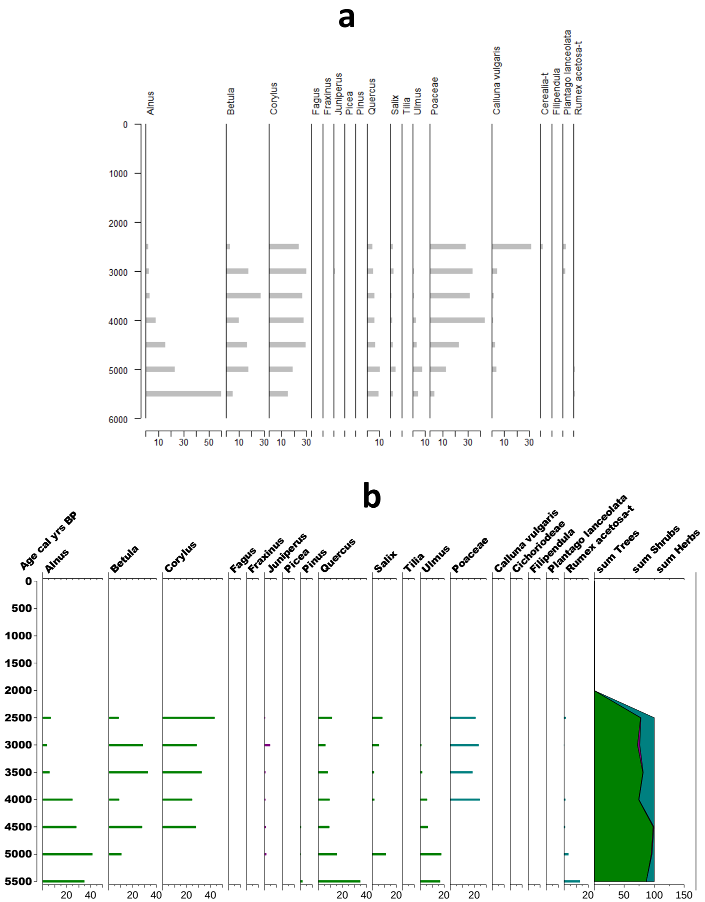


Figure 6-9: RH3 (Mighall, 2004) a) Regional and b) local pollen proportions for a selection of taxa.

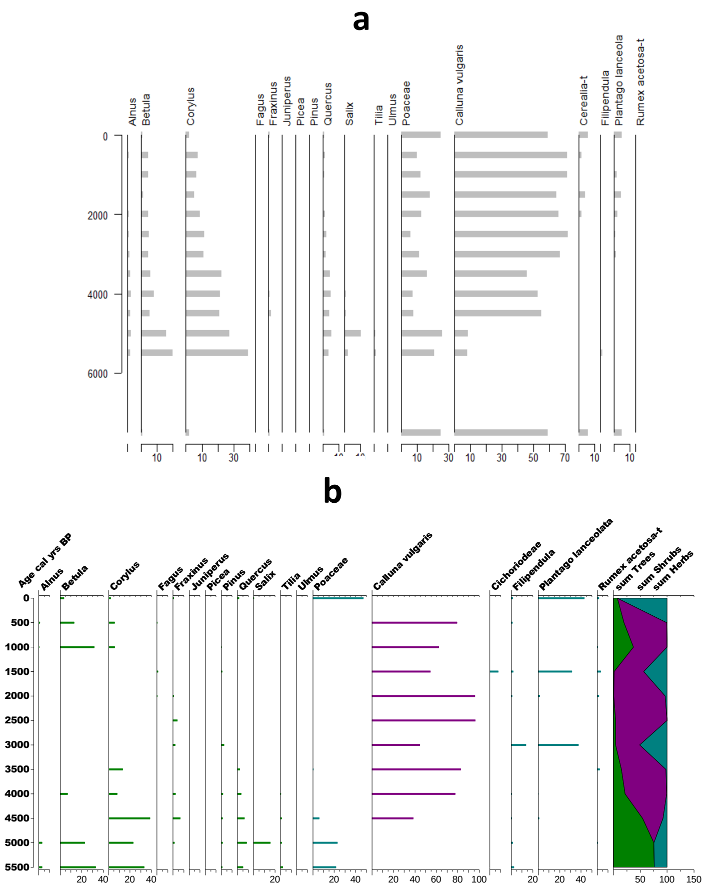


Figure 6-12: Stansheil Rigg (Cayles and Tipping, 2002)

a) Regional and b) local pollen proportions for a

selection of taxa.

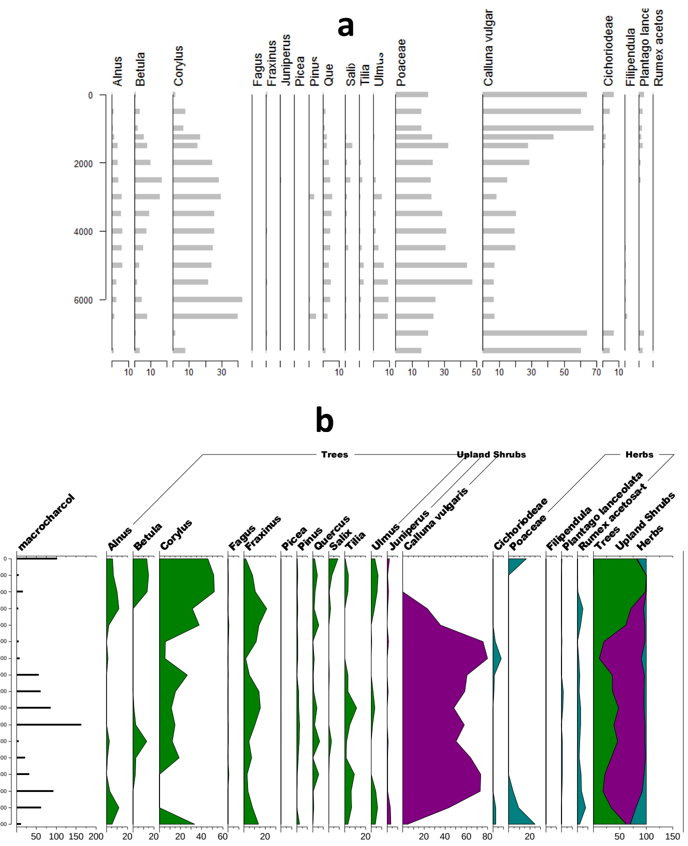


Figure 6-11: Robinsons Moss (Halsall, unpublished)

a) Regional and b) local pollen proportions for a

selection of taxa.

The REVEALs data for sites surrounding Robinsons Moss show a dominance of *Calluna* in two separate stages from 5500 and 3500 years BP. For the earlier time period 8000 to 5500 years BP there were only two records, so this time period is not well represented by the REVEALS pollen proportion estimates. The regional data do show a much later rise in *Calluna vulgaris* than the local data for Robinsons Moss using the LRA algorithm (Sugita, 2007 a, b), at around 7500 years BP. Tallis (1991) also found mid Holocene *Calluna* peaks at 8700 and 7600 years BP. This implies that Robinsons Moss could be impacted by different local disturbances than the surrounding landscape as shown in the REVEALS data or it could imply a difference in the local environmental conditions at Robinsons Moss from the other sites used in the analysis. Bluewath Beck, the only other record for 7000 years BP also shows *Calluna* to be present at this time. Further sites would be needed to confirm this as a climatically driven expansion of *Calluna*. The basal age of peat at Robinsons Moss is 9000 years BP (Tallis, 1991) indicating an early paludification process and expansion of *Calluna vulgaris* and *Sphagnum sp.* Expansion of *Calluna* from 6000 years BP in the U.K. is generally attributed to deforestation and the expansion of agriculture (Vanniere *et al*, 2008; Chiverrell *et al*, 2008; Fyfe *et al*, 2018; Gearey *et al*, 2000). Neolithic artefacts and practices appeared in Britain ~ 6100 years BP (Whittle *et al*, 2011).

Robinsons Moss and other upland peat bogs in the Peak District are sensitive to changes in environmental conditions. Robinsons Moss at 500 m a.s.l. is sensitive to temperature changes which subsequently affects the dominant vegetation. By 8000 years BP, Robinsons Moss was probably covered by *Betula* and *Salix* scrub which expanded upwards until around 5500 years BP (Tallis, 1990). Climatic conditions have a dominant role in the development of the blanket peat, which as it expands, can surround and kill the trees in the basin and then the surrounding slopes. Trees not overcome by expanding peat on the lower slopes, are also likely to have been burnt or removed by human activity. The wider region continued to be forested until around 2000 years BP where a change to a dominance of *Calluna* can be seen although tree taxa also continue in the landscape.

Regional fire

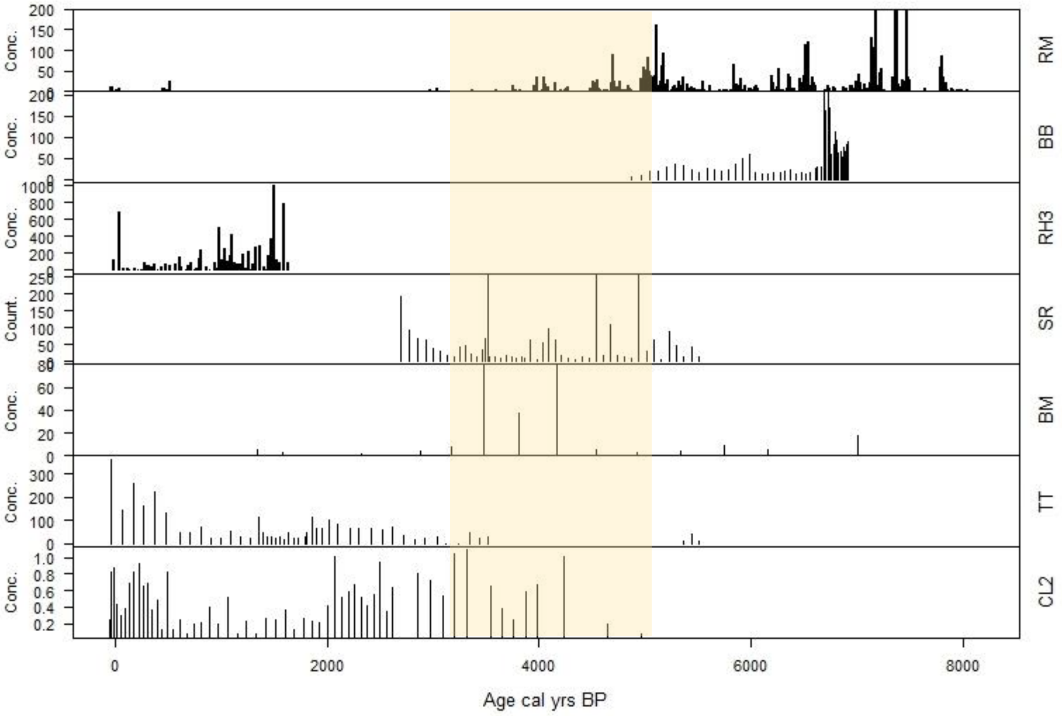


Figure 6-13: Microcharcoal and count fire records for the sites shown on figure 6-5 as examples of the temporal range of fire records in the Peak District region; Talkin Tarn (TT), Robinsons Moss (RM), Bluewath Beck (BB), RH3, Stansheil Rigg (SR), Bank Moor (BM), Talkin Tarn (TT), Crag Lough (CL2) plotted against age cal yrs BP.

Peaks in the charcoal values can be seen between 5000 and 3500 for Robinsons Moss, Stansheil Rigg, Bank Moor and Crag Lough (figure 6-13). This coincides with the Bronze Age a time period when major deforestation is thought to have occurred across the U.K. (Ryan & Blackford, 2010). In figures 6-6 to 6-12 showing the regional pollen proportions calculated using the REVEALS model (Sugita, 2007b), we can see a reduction in the percentage of tree taxa after 3500.

Each site was analysed used RDA with charcoal values as the explanatory variable.

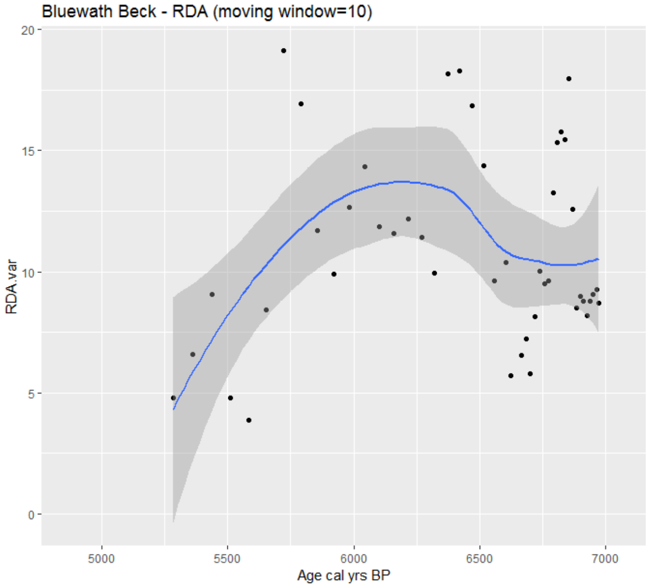


Figure 6-14: RDA analysis for Bluewath Beck using transformed pollen percentages (squared) with charcoal as the constraining variable. Points represent RDA values using a moving window (10), blue line obtained using a loess smoothing function (span = 0.3), and shaded areas represent 95% confidence limits.

Figure 6-15: RDA analysis for RH3 using non transformed pollen percentages with charcoal as the constraining variable. Points represent RDA values using a moving window (10), blue line obtained using a loess smoothing function (span = 0.3), and shaded areas represent 95% confidence limits.

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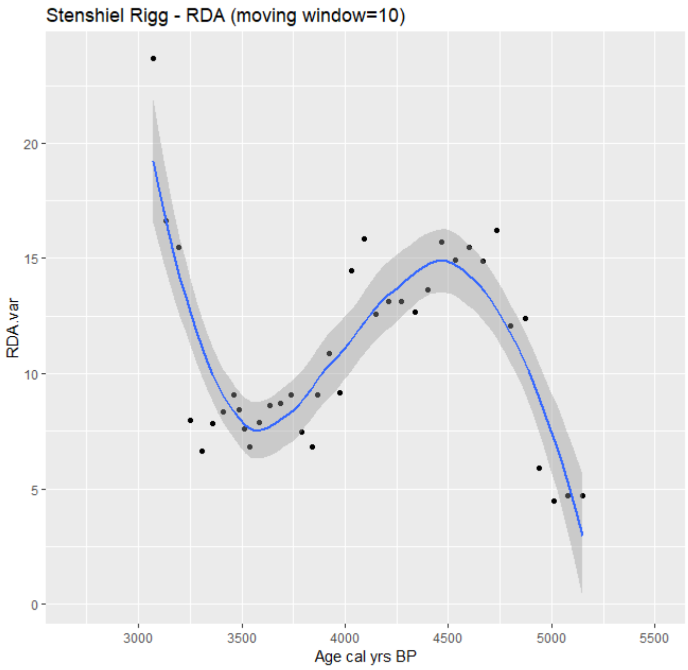

Figure 6-16: RDA analysis for Stanshiel Rigg using non transformed pollen. Points represent RDA values using a moving window (10), blue line obtained using a loess smoothing function (span = 0.3), and shaded areas represent 95% confidence limits.

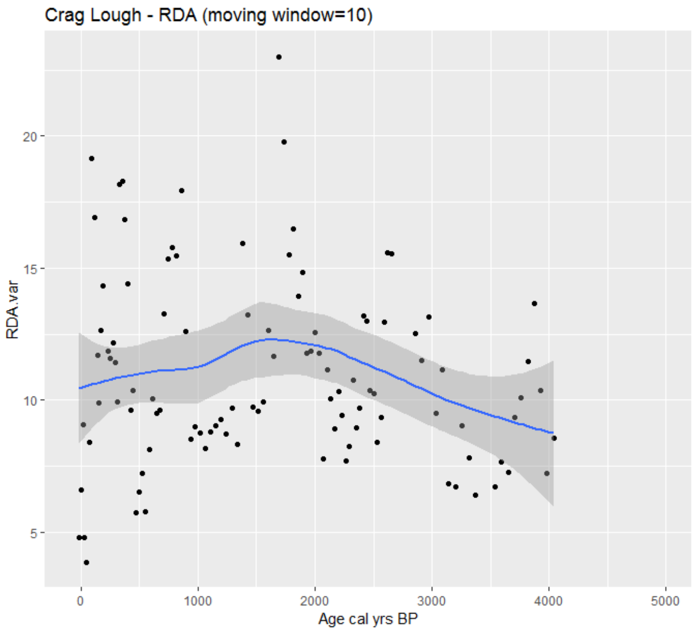

Figure 6-17: RDA analysis for Crag Lough using square transformed pollen percentages. Points represent RDA values using a moving window (10), blue line obtained using a loess smoothing function (span = 0.3), and shaded areas represent 95% confidence limits.

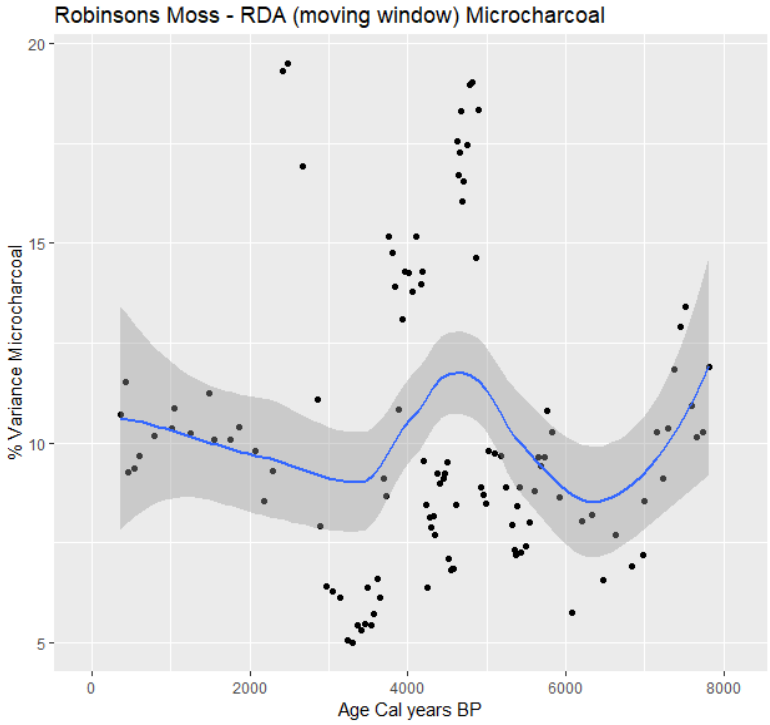

Figure 6-18: RDA analysis for Robinsons Moss using non transformed pollen percentages with microcharcoal values as the constraining variable. Points represent RDA values using a moving window (10), blue line obtained using a loess smoothing function (span = 0.3), and shaded areas represent 95% confidence limits.

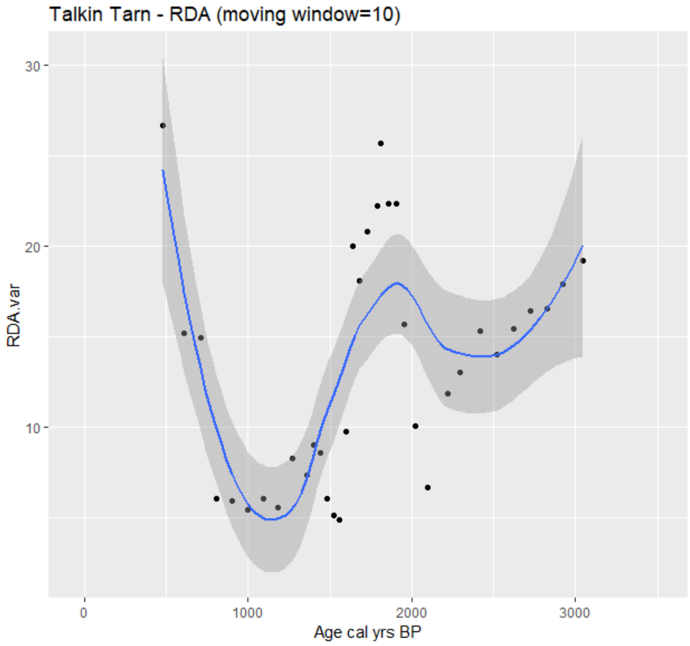

Figure 6-19: RDA analysis for Talkin Tarn using non transformed pollen. Points represent RDA values using a moving window (10), blue line obtained using a loess smoothing function (span = 0.3), and shaded areas represent 95% confidence limits.

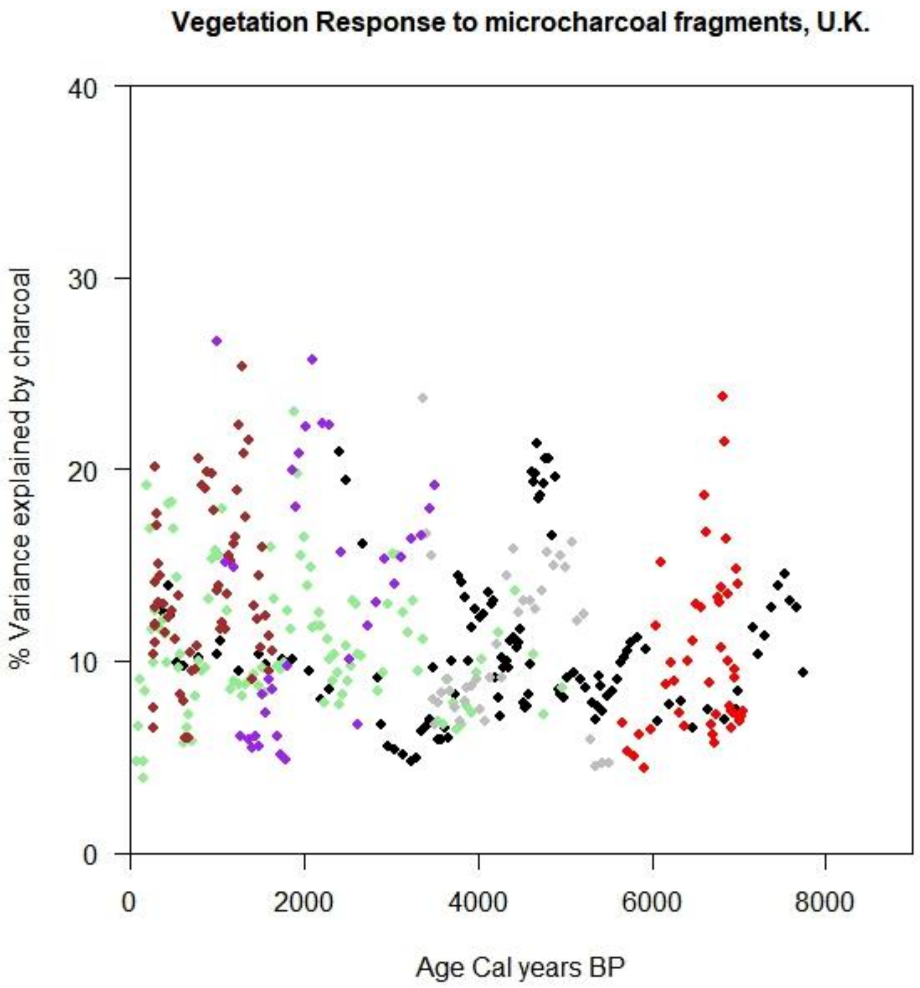

Figure 6-20: RDA values showing percentage of vegetation dynamics explained by fire for six sites; Robinsons Moss (black), Bluewath Beck (red), Crag Lough (light green), RH3 (brown), Stanshiel Rigg (grey), Talkin Tarn (purple) plotted against age cal yrs BP.

A data transformation could increase the axis length of the first DCA however, the results show the untransformed data. RDA analysis for Bank Moor was not processed as the charcoal values are at a very low resolution.

Redundancy analysis with charcoal as the constraining variable shows a consistently low percentage value for variance that explains the vegetation dynamics. The values range between 5 - 26% across all sites (figure 6-20). This shows a consistency between the sites in that disturbance by fire is not the main factor driving the ecosystems. The sites chosen have similar ecological conditions in that they are all above 240 m a.s.l. and except for Crag Lough (lake), all of the sites are peat bogs. The sites will be subject to different local conditions and disturbances such as fire events, wind throw, however there is a higher percentage of variance in the vegetation dynamics explained by fire events around 4500 years BP for both of the sites that cover that time period.

Age yrs BP	RM	BB	CL	RH3	SR	TT
1000 - 0	11.45	na	10.99	13.01	na	12.36
2000-1000	10.18	na	10.95	14.85	na	13.20
4000-2000	9.39	na	10.43	na	10.19	14.22
6000-4000	11.57	6.25	10.25	na	11.32	na
8000-6000	9.95	11.60	na	na	na	na

Table 6-3: Mean RDA values (percentage variance in vegetation dynamics explained by fire events) for 2000 year bins prior to 2000 years BP and in 1000 year bins for 2000 – present day.

Table 6-3 shows major changes in the RDA values for each site. This table highlights the range in temporal scales between sites and that the sites show local differences in the RDA values.

p < 0.01 **			
	RM	BB	CL
RH3	**	**	**
TT	**		

Table 6-4: Pairwise t test for significance between sites using mean of RDA values significant at 99% p < 0.01 (**). Blank squares indicate a non significant value.

RH3 is significantly correlated with RM, BB and Cl as shown in table 6-4. The remaining pairwise tests were not significant.

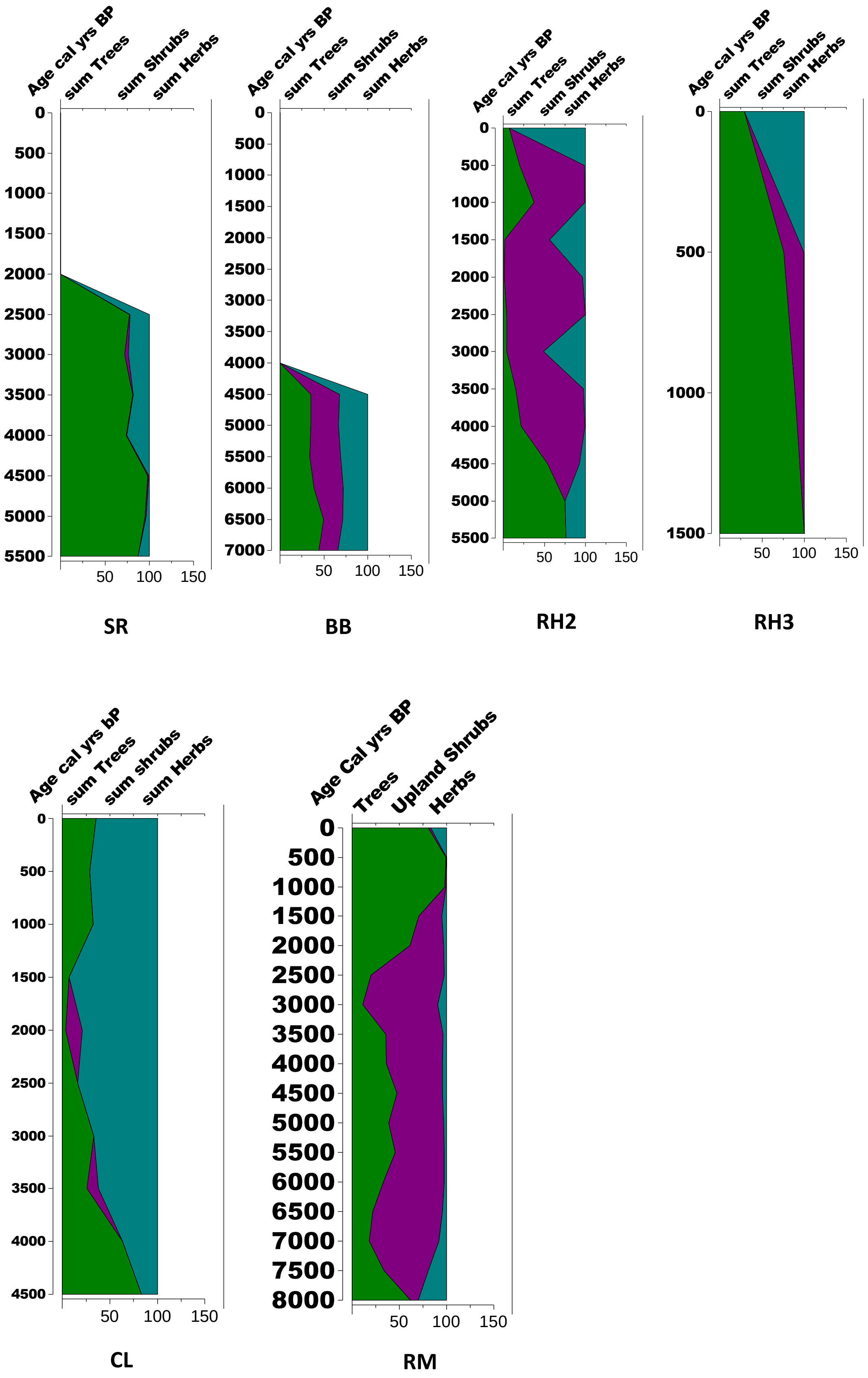

Figure 6-21: Local pollen proportions calculated using LOVE model (Sugita, 2007, b) for Stanshiel Rigg (SR); Bluewath Beck (BB); RH2 (RH2); RH3 (RH3); Crag lough (CL);

There are clearly local differences in the vegetation dynamics as shown by the pollen proportion diagrams for tree, shrub and other taxa in figure 6-21 (Simmons, 2003) discusses a patch dynamic for the moorlands of England and Wales with *Corylus* showing as a strong feature. Finsinger *et al* (2006) discusses that *Corylus* expand when there is high seasonality, summer drought and frequent fires. This study uses only a few datasets, that cover a disparate temporal range so no definitive conclusion can be made about the changes in the tree, shrub and herb taxa, however *Calluna* shows a clear presence in these upland areas throughout the middle/late Holocene, 6000 – 4000 years BP.

6.6 Discussion

This chapter will provide evidence in answer to the second question for the thesis:-

B How does the Holocene fire regime at Robinsons Moss, Peak District compare with the regional fire regime across the Peak District?

The sites used in this analysis cover a geographical range from Stanshiel Rigg, Scotland to Robinsons Moss, South Peak District (60 1 000 N to 36 8 800 N). Other sites that were considered are shown on the site map, but these sites were rejected for various reasons such as the availability of pollen percentage data but not charcoal fragment data, digitised record instead of raw data record.

The vegetation response analysis (RDA) shows that the percentage variance explained by fire events during the Holocene for the Peak District area does not exceed 26% at any time period (figures 6.21). This implies that fire is not the dominant driver and that there is another factor or factors driving these ecosystems that would explain the remaining 74% variance in the vegetation dynamics. This percentage could be reduced due to the wide spatial scale of the microcharcoal and pollen percentages creating a less direct relationship to the local area surrounding the sites.

The initiation, establishment and growth of peat bogs in the north of England are thought to have occurred during at least two separate time periods. At some sites, under suitable climatic and geographic conditions, peat initiated around 9000 – 8000 years BP (Tallis, 1987, 1990). A second major phase of initiation is thought to have occurred around 5000 years BP (Fyfe *et al*, 2018). This second phase is thought to be linked to an expansion in population across the U.K. with subsequent disturbances to ecosystems such as deforestation and agricultural practices (Kaplan *et al*, 2017; Woodbridge *et al*, 2014; Lomas-Clark *et al*, 2004; Ellis et al, 2001) . This issue of different drivers for these different time periods is discussed in Simmons book ‘The moorlands of England and Wales’ (2003). Here he favours the idea that climate is also driving these later peat initiations. The expansion of tree taxa that occurred across the U.K. during an increase in temperature, during early Holocene meant that all but the highest fells had some tree or shrub cover by 8000 years BP (Tallis, 1991). This included those areas with peat or base-rich soil substrates. *Alnus*, *Betula*, *Corylus* and *Salix* will thrive in damp or wet places and on peat bog hummocks, so these taxa were dominant around wetlands. Holocene climatic conditions are difficult to determine at a regional level for the U.K. as shown in the low level of agreement in temperature and precipitation datasets for the U.K (Schulting, 2010). The sites used in this study to determine regional pollen proportions using the REVEALS model (Sugita, 2007a), are all above 240 m a.s.l. and within a geographical zone that will have generally been exposed to similar regional climatic conditions. As only two of the sites go back to pre-6000 years BP; Robinsons Moss and Bluewath Beck, any observed trends are more difficult to establish for this time period, although both sites show the early presence of *Calluna vulgaris.*

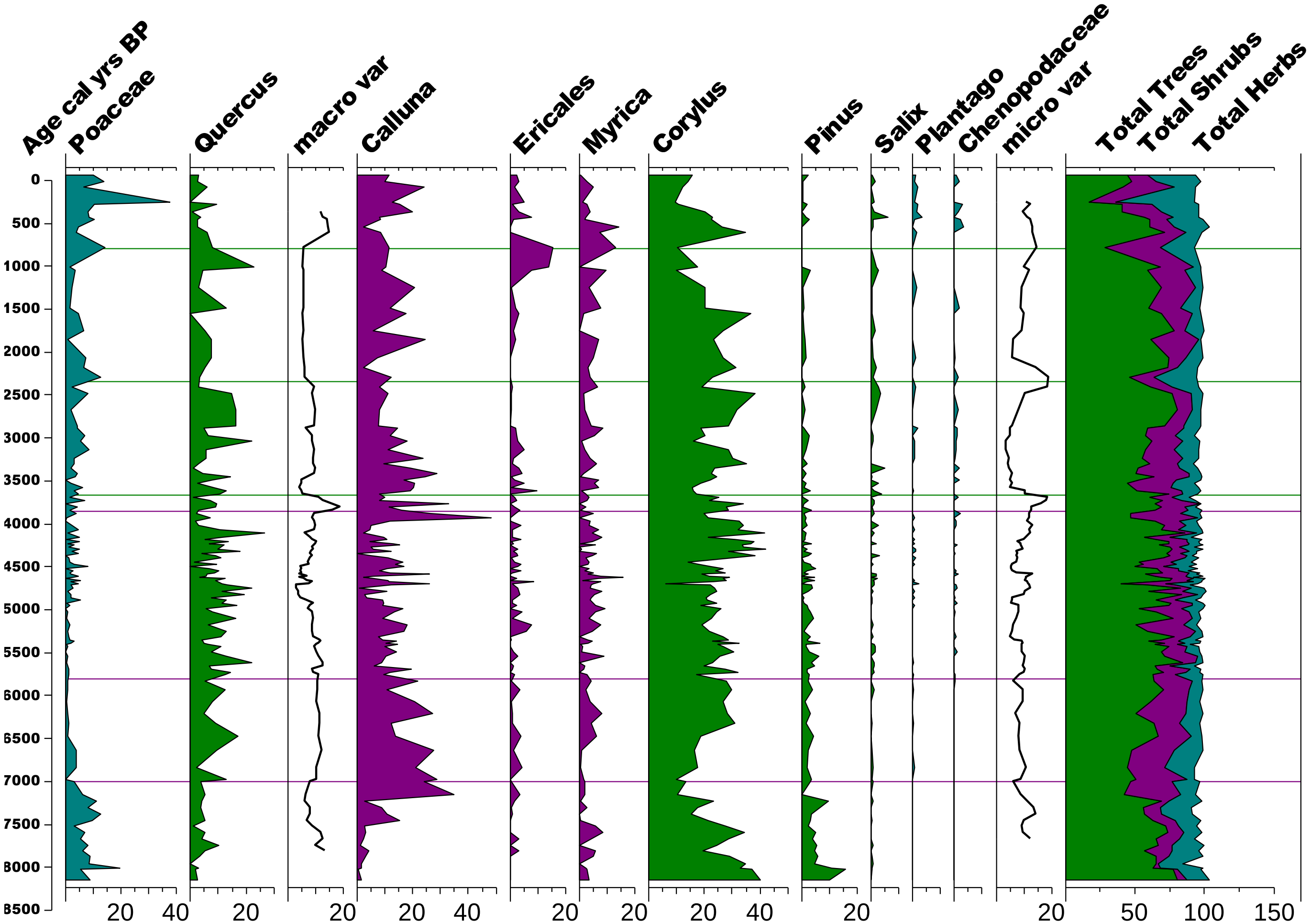

Figure 6-22: Pollen and charcoal diagram (Grimm, 2011) for Robinsons Moss showing pollen percentages for a selection of taxa with RDA values for macrocharcoal and microcharcoal.

Two general trends can be seen across the regions. The LOVE modelled data (Sugita, 2007b) indicate a general presence of shrubs during the mid/late Holocene, 6000 – 4000 years which reduces in quantity post 2000 years BP. We can also see that *Alnus*, *Betula* and *Corylus* are local taxa present at most of the sites for all of the time periods. As these are trends across several sites, it could indicate that the vegetation cover of this region is driven by climatic conditions. Correlation values for a selection of tree and shrub taxa with fire events for Robinsons Moss using macrocharcoal can be seen in table 5-4 and for microcharcoal, table 5-3. Some taxa such as *Calluna* are adapted to fire environments and quickly expand post fire. We saw in chapter four that microcharcoal values (> 50 microns) were significantly positively correlated with *Calluna vulgaris* (table 5-3) indicating a regional expansion of *Calluna*. Shade tolerant tree taxa such as *Tilia* and *Ulmus* showed negative correlation with high macrocharcoal fragments at Robinsons Moss (figure 5-17) although not a significant correlation. In other studies for the U.K. *Sphagnum* taxa have been shown to regenerate rapidly after a fire event (Clymo & Ducket, 1986) and can lead to peat expansion. Pitkanen (1999) concluded that burning the upper layer of peat can radically change the vegetation and that a dry season with a decrease in the water table creates the favourable conditions necessary for a peatland fire. These findings show the short and long term effect of fire events on vegetation assemblages, but what long-term impacts on the vegetation dynamics of periods with a high fire return interval and for time periods with a low fire return interval can be seen across the Peak District?

In this study, RDA has been employed to examine the vegetation response to fire events during different millennia for several sites across the Peak District region. Although the site datasets cover very different and disparate time periods, a regional trend can be seen in that there are high charcoal values around 4500 years BP, during the Bronze Age (figure 6-13). There is also a trend across all sites for the range of percentage values for variation in the vegetation dynamics explained by fire (figure 6-14 to 6-19). This is 5 – 26% implying that factors other than fire are driving the ecosystems and can explain the remaining 74% of variance in the vegetation dynamics. This maximum value is within close range of the study done by Colombaroli *et al* (2010) for the Mediterranean region where the results showed that fire could account for between 26 and 35% of vegetation variance during parts of the Holocene. The study site is Mediterranean and at a higher altitude, so there would be dissimilarities in the type of vegetation and climatic susceptibility to fire. Regionally, as shown by the microcharcoal record, during certain time periods, 8200 – 7000 years BP; 5000 – 4000 years BP and during the last 800 years, there are peaks in the RDA values. Are these peaks the result of lagged response to changes in climatic conditions creating suitable conditions for fire and how much is due to human activity? There is some correlation between specific taxa such as Poaceae *and Calluna* *vulgaris,* however, although 77% of variance in vegetation dynamics is unexplained, fire can be seen as a relatively important factor in driving vegetation dynamics to its current state. It is interesting to compare this result with other studies in northern Europe. Colombaroli in his study at Lago di Massaciuccoli, a coastal lake in Tuscany, found that 32.2% of the variation in the vegetation dynamics would be explained by fire using RDA analysis and for the savannah grass - steppe area surrounding Lake Simbi, Kenya the maximum value of RDA is 30%. For lakes in the southern boreal forest zone, Fennoscandia, Kuosmanen *et al* (2016) also used RDA to show that fire explained 0.5% of the variance for the lakes and for small forest hollows, 1.1% is explained by fire. These are very different environments and environmental conditions, so vegetation assemblages will vary temporally and spatially. However, this low value could indicate the dominance of changes in climatic conditions that the trees, shrubs and herbs are responding to, both across the Peak District and also across Europe with fire events as a response to changes in the vegetation dynamics. In the Kuosmanen *et al.* (2016) study, indeterminable variation ranged between 38 – 59% despite inclusion of climate. Fire, human population size and site factors in their analyses, showing that palaeoecological data are inherently noisy. However, the value of percentage variance explained by fire events during the Holocene for the Peak District of up to 26% found in this thesis are high for northern European ecosystems, even in comparison with the fire-prone boreal forest.

There is a reduction in the variance explained by fire from around 20 – 25% to around 9 – 11 % from 4000 – 2000 years BP. This coincides with a change in climatic conditions to wetter and colder than in previous millennia. It is difficult to achieve agreement in fire-vegetation relationships at the regional level, as individual local conditions will also have a strong influence, however these trends suggest that changes in climatic conditions are driving these types of ecosystems over long time periods. If local environmental conditions and disturbance events had a greater effect on the range of percentage values and there was no temporal consistency across the sites, then it would be less likely that climatic factors were the dominant driver in these upland moorland sites and more likely that human activity had a greater influence in driving the vegetation dynamics. It was shown in chapter four that it is likely that Mesolithic people were using the resources available in the Peak District and similar locations. Judith Turner explores the impact of Mesolithic people in her work on the north York Moors (Turner, 1993). This activity, which would include the use of fire, was more likely to occur during phases of warmer drier conditions and forest expansion implying that human activity during these early millennia is therefore likely to be connected to changes in climatic conditions, adding a complex layer that makes it difficult to disentangle human activity from climate change. The increase in vegetation response to fire from 2000 years BP to the present day (RDA variance using microcharcoal) shown in figure 6-22 could reflect a change in land use that is seen generally across Europe during the late Holocene (Molinari *et al*, 2013) with fire being used to clear forest taxa, again showing the importance of fire.

There are indications of a pattern of wet/dry shifts seen in the vegetation and fungal assemblages for Robinsons Moss. The XRF results show some indication of the impact of fire events on the soil chemistry. These disturbances, although of low impact, are still important factors in ecosystem dynamics and work in combination with the changes in climate conditions that have ultimately driven upland peatland ecosystems over long time periods.

As is often the case, when there is a combination of factors that can all potentially make dramatic changes to ecosystems, it is most difficult to determine what is the dominant factor and further long-term studies are still needed. This type of information is vital in developing our understanding of fire prone ecosystems and to understand ecosystem response to fire events over long time scales. We can see that fire events are less important in driving the ecosystem than changes in climatic conditions, however, the use of fire by people is also driven by climatic conditions during the early and middle Holocene. Upland ombrotrophic peatlands respond to changes in the water table and fire events respond to the subsequent changes in the vegetation dynamics. Long-term ecosystem responses to episodic events are still linked with climatic conditions. More detailed long-term studies for fire prone habitats such as those in the Peak District are still needed if we are to form cohesive datasets that allow us to see these long-term trends.

Regionally, the pollen proportion estimates show a change in dominance between tree taxa and ericaceous taxa particularly around 5500 years BP. This occurs earlier at Robinsons Moss indicating local differences in successional changes. The geochemistry shows the transition to a peat bog and the impact of fire events on the soil chemistry. This confirms the benefit of a multiproxy study for exploring the complexities of upland mire ecosystems in the U.K.

It is difficult to say whether peat development would have happened without the impact of early people due to the complexity of the feedback mechanisms and time lag for vegetation response. Research is showing that climate is the dominate driver for mire systems (Fyfe *et al*, 2013; Lawson *et al*, 2008). Fire needs biofuel and there is certainly evidence for forest taxa in upland areas of the U.K. during the early and middle Holocene. Simmons *et al* (2003) states that as the upper limit for forest growth is reached, *Corylus* scrub layer on the higher slopes would likely shift to *Betula* and *Salix* with increased wetness and soil acidity. Simmons wonders whether the fire events recorded by the presence of charcoal fragments seen in many UK peat cores are natural, lightning set or ignition was caused by people. This is a difficult question to answer, however by comparing local and regional data for similar sites within a region, we can identify if there are local differences in the vegetation dynamics or regional similarities. For the Peak District and surrounding upland areas, there are certainly local differences and the RDA values in this research show a consistent level of response by vegetation to fire events indicating a region wide climatic influence.

6.7 Conclusions

1 The percentage range for fire events that explains the variance in vegetation dynamics across the Peak District region is consistently between 5 and 26% for the last 8000 years. Although this implies that fire is not the dominant long-term driver of vegetation dynamics, it is still an important factor and comparable to its role in other European fire-prone ecosystems. As there is some regional consistency, this would imply that climate is the dominant driver of the vegetation dynamics.

2 The application of the LOVE programme (Sugita, 2007a, 2007b) has shown the presence of shrub vegetation 6000 – 5000 years BP, but also the early dominance of shrubs at upland sites where peat was initiated probably by natural environmental conditions around 9000 – 8000 years ago as shown in Tallis (1987, 1999). Both of these occurrences are likely to be a response to changes in climatic conditions in a fire-adapted ecosystem.

3 From 6000 – 3000 years BP, differences in local conditions means local variation in the timing and intensity of fire events.

4 There is a general trend of reduction in fire events from 3000 – 1500 years BP. This would fit with a change in climatic conditions seen across Europe to wetter colder conditions during this time.

5 There is a trend of increasing fire events during the last 2000 years.

6 The impact of Holocene fire events varies under different local conditions. Fire is more important in the coastal lake area of Tuscany than in the boreal forest of Fennoscandia. Yet at Robinsons Moss values for percentage variance explained by fire events are intermediate between boreal forest and Mediterranean values. These percentage values have not yet been found to exceed 33% in any of these fire-prone regions showing that fire has not been the long-term dominant driver in any European ecosystem during the Holocene.

There are differences in the pollen proportions calculated using the LOVE programme (Sugita, 2007 a, b) which was also seen in Fyfe (2018). The RDA values however do show a trend across the sites that fire has a greater effect on the vegetation dynamics of the Peak District from 5000 – 4000 years BP which would indicate a regional climatic influence on the vegetation and a response of increased fire events to the climatic conditions.

Chapter 7 The reconstruction of past forest dynamics over the last 13,500 years in SW Sweden

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The Holocene; 28; 1791-1800

7.1 Abstract

Evidence for unbroken continuity of tree taxa over the last *c.* 13,500 years is presented from a biodiversity 'hotspot' nature reserve in south-west Sweden. Forest composition, continuity, fire and disturbance events are reconstructed using palaeoecological methods. A lake record reveals that *Pinus sylvestris, Betula* spp., *Salix* spp., *Populus tremula* and *Hippophae rhamnoides* were the initial trees scattered in a semi-open, steppe environment. This developed into forest with *Pinus, Betula, Corylus, Alnus, Ulmus* and *Populus* with evidence for frequent fires. Deciduous trees became more significant as fires became less frequent and *Quercus, Fraxinus* and *Tilia* expanded. Fire frequencies increased again in the Bronze Age probably associated with anthropogenic use of the forest, and the first *Fagus sylvatica* pollen was recorded. Burning continued through the Iron Age, but charcoal is briefly absent for a period often referred to as the 'Late Iron Age Lull'. The forest re-expanded with successions involving *Juniperus*, but with an altered composition from the earlier mixed deciduous community, to one dominated by *Fagus*. This is coincident with the first pollen records for *Picea abies*. The early Holocene mixed forest with frequent low-intensity fires is potentially associated with the greatest diversity of red-listed insect species. Forest continuity and the fragmented reservoir populations of old deciduous trees in the *Fagus*-dominated forest today are likely to have been critical in preserving the present-day, species-rich, rare epiphytic flora, wood-inhabiting fungi and invertebrate communities. As many of these forest fragments may become more vulnerable with future climate change, tree diversity with some disturbance may become essential for survival of the endangered saproxylic species.

Keywords ; biodiversity hotspot, fire, forest, long timescales, pollen, Scandinavia

7.2 Introduction

A widespread biotic homogenization of forests has taken place in Europe during recent centuries, particularly affecting local tree diversity. One example of such homogenization is the 'borealisation' of southern Scandinavia, which has been driven by both natural forces, such as climate change, and cultural forces, including commercial forestry operations (Lindbladh et al, 2014; Seppä et al, 2009). The replacement of diverse deciduous forests by monocultures of *Picea abies* is associated with the local loss of many species of insect, bryophyte and lichen that are dependent on *Quercus, Tilia, Populus, Alnus* and other trees (Jonsell et al, 1998). The late-Holocene spread of *Fagus sylvatica* through northern Europe has also resulted in a reduced tree diversity throughout large areas of forest in Germany, Denmark and southern Sweden, and this change in forest composition has been driven by combinations of natural and anthropogenic factors (Bradshaw et al, 2010; Giesecke et al, 2011). These major forest changes pose a challenge to nature conservation. If tree diversity is a valid target for management of biodiversity, what type of forest composition should be encouraged, and which management tools are appropriate? For restoration purposes, managers would like to know how the present forest composition has developed from earlier conditions and what likely future compositions may develop (Higgs et al, 2014). If current composition differs from the past, how, why and at what rates have these changes occurred? Do past conditions indicate appropriate forest compositions for the future that would maximize diversity and minimize the legacy of anthropogenic modifications? These questions can be addressed through the reconstruction of past forest dynamics using palaeoecological techniques yet have only rarely been approached in this way (Willis et al, 2010).

Palaeoecological investigations can provide relevant information about long-term changes in species diversity, forest continuity, types and frequency of disturbance and the extent of human impact (Bradshaw et al, 2015). There is still debate and uncertainty about the influence of anthropogenic activities and the role of fire on past forest composition and dynamics of southern Scandinavian forest that could be partially resolved by a complete Holocene record from this region (Bradshaw et al, 2010, 2015; Clear et al, 2014; Molinari et al, 2013). All this information is of value in planning successful forest conservation measures (Dietl et al, 2015).

In this paper, we investigate the long-term history of a forested landscape in south-west Sweden (Figure 7-1). Here, the building of nature reserves has been designed to facilitate the restoration of natural forests over large areas (Bengtsson, 1999).

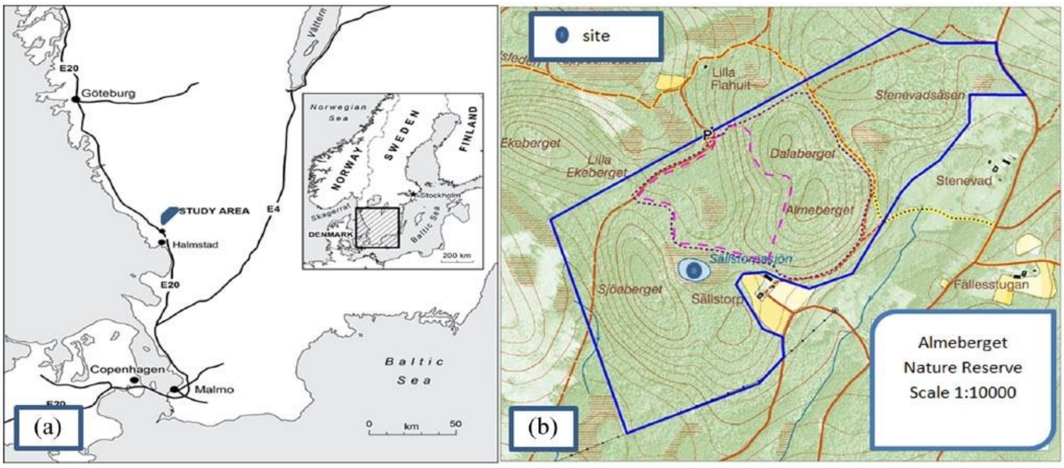


Figure 7-1: Location map showing (a) the position of Almeberget Nature Reserve in south-west Sweden and (b) the location of the lake within the reserve.

Such forests, detailed on maps from the 1600s (Fritz, 2009), are in Sweden taken to mean ‘Old Forest’ with long continuity. The maps show that this forest reserve used to be part of a much larger *Fagus* forest, after which there was a sharp decline in areal extent over the following centuries. We present sedimentary pollen assemblages and charcoal influx over the last 13,500 years from a small lake (Figure 7-1). Continuous late-Glacial and full Holocene vegetational records are limited from this part of the Scandinavian Peninsula. Bradshaw et al. (2015) discussed the relative importance of forest continuity and disturbance dynamics as controls on current biodiversity in north-west Europe and concluded that dynamic processes were of greater significance. Our major purpose is to test the hypothesis that the perceived natural value of rich epiphytes, wood-inhabiting fungi and invertebrate communities so valued today is associated with long-term forest continuity and minor anthropogenic impact over long timescales. We therefore examine the long-term balance between forest continuity and dynamic processes in a currently protected area.

7.3 Materials and methods

7.3.1 *Study setting*

The 70 ha forest reserve at Almeberget is in the temperate vegetation zone of south-west Sweden (Ahti et al, 1968), in low hills (85–150 m a.s.l.) at the edge of the southern Swedish highlands. It is approximately 15 km north-east of the town of Halmstad (Figure 7-1).

The forest reserve today is dominated by *Fagus*, but there are some mature *Pinus sylvestris* (pine), *Quercus robur* (oak) and *Sorbus aucuparia* (rowan). Younger areas of *Alnus* spp. (alder), *Pinus* and *Betula* spp. (birch) can be found in the valleys, while *Salix* spp. (willow) and *Populus* *tremula* (aspen) are less common. The oldest *Fagus* trees, which act as hosts for many of the present-day red-listed species (Fritz, 2009; Lindström, 2012) including the extremely rare and endangered *Pertusaria velata* (Fritz and Malmqvist, 2014), appear as large, slow-growing individuals. They date from the late 1790s and into the early 1800s, and there is abundant coarse woody debris on the forest floor in the form of both stumps and trunks. The forest is allowed to develop without direct intervention. Peripheral forests consist of younger, thinned *Fagus* enclaves alongside forest plantations (mainly *Picea*), which are being gradually dismantled and naturally regenerating *Picea* is being removed.

Sällstorpssjön (56°51′1.75″N, 12°53′32.75″E) is a kettle hole lake *c.* 0.5 ha in size in a bowl-shaped basin (Figure 7-1b). The bedrock is largely pre-Cambrian granite. The site is above the highest marine limit, which in this part of Sweden is *c.* 65 m a.s.l. (Berglund, 1995). The region can be considered to have a maritime climate with high rainfall (*c.* 1000 mm p.a. average 1975–1990) and moderate temperatures (mean January and July temperatures are from −2.4°C to 15.4°C; Syren, 1995).

7.3.2 *Fieldwork*

The lake sediment was cored through the ice with a 10-cm Russian corer. The sediment/water interface was at 450 cm below the ice. The wetter area immediately around the lake was surveyed and consisted mainly of mixed forest (Table 7.15), while the upland slopes were drier and dominated by *Fagus* or planted conifers. There are no inflows to the lake (Figure 7-1b).

7.3.3 *Laboratory methods*

Six thin sediment samples were sent to the AMS dating facility at Lund University for analysis. All radiocarbon dates were calibrated to a calendar year timescale (cal. BP), where BP refers to 1950. Total concentration of atmospherically deposited lead (Pb) was determined using the Bruker S2 Ranger X-ray Fluorescence Spectrometry (XRF) spectrometer (University of Liverpool). Samples were taken at 5 to 10 cm intervals, freeze-dried at −55°C and then ground into a powder. Peak values for Pb were correlated with dated values from nearby sites (Bindler et al, 2011). An age– depth relationship (Figure 7-2) was drawn up with both radiocarbon and Pb dates (Table 7.16), using CLAM software (Blaauw, 2010).

Pollen samples of 1 cm^3 were prepared using standard techniques (Berglund and Ralska-Jasiewiczowa, 1986) with a sampling interval of either 4 or 10 cm throughout the sediment profile. *Lycopodium* tablets were added to allow pollen concentration and influx calculations. Slides were counted at a magnification of 400× and the pollen diagrams were drawn up as a percentage of the sum of terrestrial pollen, excluding aquatics and spores (Figures 3 and 4). The pollen diagrams were divided into periods where major changes in vegetation could be seen. Samples for percentage loss on ignition were burned at 450°C for 4.5 h.

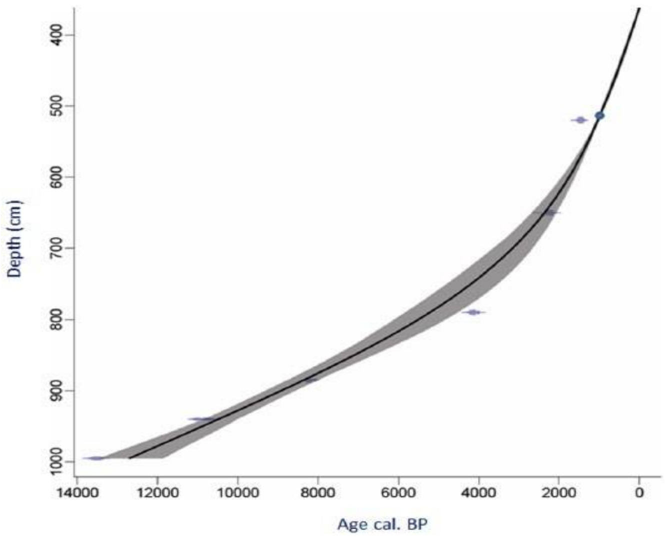


Figure 7-2: Age-depth relationship for sediments from Sällstorpssjön.

Trees and shrubs	Herbs and ferns
Fagus sylvatica	*Rubus chamaemorus*
Quercus robur	*Plantago major*
Betula pendula	*Molinia caerulea*
Pinus sylvestris	*Agrostis canina*
Picea abies	*Hypericum maculatum*
Alnus glutinosa	*Galium sp.*
Sorbus aucuparia	*Scutellaria sp.*
Frangula alnus	*Eriophorum angustifolium*
Salix aurita	*Eriophorum vaginatum*
Juniperus communis	*Juncus effusus*
Calluna vulgaris	*Carex panicea*
Vaccinium oxycoccus	*Carex rostrata*
Vaccinium myrtillus	*Carex lasiocarpa*
Erica tetralix	*Scheuzeria palustris*
	Luzula sylvatica
	Deschampsia flexuosa
	Veronica officinalis
	Brassica sp.
	Rhynchospora alba
	Athyrium filix-femina
	Gymnocarpium dryopteris
	Caltha palustris

Table 7-1: Species recorded around the lake.

Contiguous 2 cm^3 samples were extracted for charcoal analysis, measured out using water displacement, into test tubes of distilled water. Charcoal pieces larger than 250 µm were counted, and the area (area/cm^2/year) for each unit was estimated using image analysis techniques developed by Mooney and Black (2003) and converted into influx values using the age–depth relationship (Figures 7.2 and 37.). A statistical analysis of the charcoal data was carried out using the charcoal accumulation rate (CHAR) program (Higuera et al, 2007) to determine 'background' and 'peak' charcoal values with peak magnitude values identifying locally important fire events (Figure 5). The raw charcoal data (units/cm^2/year) were first interpolated to 68-year time steps, a value that corresponds approximately to the median temporal resolution of the entire record (Higuera et al, 2011) to reduce biases in the ability to detect fire events due to variable sample resolution within the record. The resulting interpolated data were then decomposed into background (BCHAR) and peak components with a locally weighted regression robust to outliers, using a 1000-year window. BCHAR was removed by subtraction to obtain a residual series of 'peak' events. A Gaussian mixture model was then used to separate the high-frequency component within each overlapping 1000-year portion of the record into 'noise' and 'peaks', the peak component being the 99th percentile of the noise component. In this way, an individual threshold was calculated for each sample. While the noise component reflects natural and analytical effects (e.g. sediment mixing, sampling), charcoal peaks, shown as red crosses, are assumed to reflect the occurrence of local fire events that are likely to be related to the occurrence of one or more local fires occurring within ca. 1 km from the site (Higuera et al, 2007). Fire history was also described by quantifying the variation of fire return intervals (FRIs, years between two consecutive fire events) and fire frequency over time, smoothed using a locally weighted regression with a 1000-year window (Figure 7-5). These numerical treatments were carried out using the CharAnalysis program (Version 1.1, available online at http://phiguera.github.io/CharAnalysis/). The changing proportion of the vegetation variance through time explained by the charcoal data was calculated using Redundancy Analysis (RDA; Thöle et al. 2016; Figure 6).

7.4 Results and interpretation

Initial vegetation, scattered trees in a semi-open landscape (13,500 cal. BP)

The vegetation reconstruction from the oldest part of this record suggests that light-demanding taxa such as *Juniperus, Empetrum*/ Ericaceae, Poaceae, Cyperaceae, *Artemisia* and Chenopodiaceae were growing on possibly unstable soils, interspersed with scattered trees of *Pinus, Betula, Populus* and *Salix* (Table 7.17; Figures 7.3 and 7.4). This is a similar picture to other parts of southern Sweden at this time (Berglund, 1979; Björck and Möller, 1987).

	Depth (cm)	^{14}C yr BP	Cal. BP	Probability
Pb date	510–511		950	
LuS 9025	520–521	1570 ± 50	1353–1552	95.0%
LuS 9026	650–651	2235 ± 50	2144–2344	95.0%
LuS 9027	790–791	3765 ± 50	3978–4293	94.9%
LuS 9028	885–886	7380 ± 60	8044–8339	95.0%
LuS 9029	940–941	9520 ± 50	10,648–11,105	91.6%
LuS 9185	995–996	11,655 ± 65	13,334–13,707	95.0%

Table 7-2: Radiocarbon and Pb dates calibrated into calendar years BP using CLAM software (Blaauw, 2010).

The threshold PAR value for the presence/absence of *Pinus* in the immediate vicinity is 500 grains/cm^2/year based on modern-day tree-line pollen traps (Seppä and Hicks, 2006). *Pinus* (PAR) values of between 500 and 1700 grains/cm^2/year at this site suggest local presence of *Pinus* (Figure 7-3). Indicator taxa such as *Hippophae rhamnoides* (sea buckthorn), associated with minimum mean July temperatures of 11°C (Figure 7-3), and pollen of *Filipendula* and *Juniperus* (Figures 3 and 4), associated with temperatures of near 10°C (Isarin and Bohncke, 1999), suggest a certain degree of warmth.

Cold steppe conditions dominated by herbs and shrubs (12,700 cal. BP)

A brief period of colder and drier conditions on a European scale between approximately 12,700 and 11,700 cal. BP (Rasmussen et al, 2006) is reflected at this site by decline in pollen of *Pinus* and an increase in herbs (Figures 7.3 and 7.4). Glacier activity increased in western Norway (Nesje, 2009), a cold precipitation period with increased snow-bed communities is reported on land (Seppä et al, 2002) and the ice sheet on the Scandinavian Peninsula re-advanced (Anjar et al, 2013). Pollen-based temperature reconstructions from the Norwegian Barents Sea Coast suggest dry conditions, such as can be observed in modern arctic deserts (Seppä et al, 2008).

At this site, the organic sediment content decreases, total pollen concentration falls from 605,698 to just over 40,000 pollen/cm^3 (Figure 7-3) and the landscape is likely to have become more open.

Fire-adapted boreal forest (11,700 cal. BP)

The palaeofire reconstruction over the last *c.* 13,500 years using the macro area/volume charcoal count data, and the results from the CHAR analysis, can be seen in Figures 3 and 5, respectively. The first fire peak identified (Figure 5a) is close to what is the likely Younger *Dryas*/Holocene transition. The tree pollen response at the beginning of the Holocene *c.* 11,700 cal. BP appears to be stepwise (Figure 7.3) and may be driven by either climatic warming or immigration of the tree species to the region (Giesecke et al, 2011). The previously more open communities were gradually replaced by shrubs and trees, including *Juniperus, Betula, Pinus* and *Populus*. The organic sediment content shows a threefold increase (between *c.* 11,700 and 9700 cal. BP), suggesting catchment stabilization. Evidence for early Holocene climatic warming is indicated by the aquatic plant record (Hu et al, 1996), particularly megaspores of *Isoetes lacustris* (Figure 7-4), where rapid population increases suggest nutrient-rich conditions and rising summer temperatures. At the present day, the minimum temperature necessary for germination success of *Isoetes lacustris*, common in oligotrophic lakes, has been shown to be 12°C (Čtvrtlikova et al, 2014) for 119 days during summer months. Flowering and fruiting of water plants in early Holocene lakes is known from many localities where there is sudden input of base rich water from rejuvenated soils (Birks and Birks, 2008). Other aquatic vascular plants recorded are *Potamogeton, Myriophyllum* and *Typha* (Figure 7-4), which, when compared with sites in Poland, central Germany, Belgium and France, suggest that temperatures rapidly approached 13°C (Isarin and Bohncke, 1999).

Hemi-boreal forest with high tree diversity and frequent fires (8500 cal. BP)

Hemi-boreal forest conditions follow, with high tree pollen diversity comprising both temperate and boreal species (Figure 7-3), and repeated fire events (Figure 7-5). *Ulmus* and *Alnus* pollen values increase prior to the expansion of *Quercus, Fraxinus* and *Tilia. Corylus* pollen frequency is temporarily reduced, a phenomenon known from many pollen sites in Europe at this time (Giesecke et al, 2011), but quickly returns to close to its former values (Figure 7.3). The disturbance-adapted *Populus* is an important forest

The low values for most herbaceous pollen and fern spores (Figures 7.3 and 7.4) after *c.* 8500 cal. BP suggest low light conditions on the forest floor and a rather dense forest structure dominated by a wide variety of deciduous trees and shrubs. The gap in

fire peaks (Figure 7-5a) probably reflects the development of a temperate forest ecosystem with mixed, mainly deciduous pollen taxa recorded (Figure 7.3). The present-day dividing line between the temperate part of southern Scandinavia and the mixed boreal– deciduous or ‘hemi-boreal’ zone became established by *c.* 7000 cal. BP (Berglund et al, 2008).

Closed temperate mixed forest dominated by deciduous trees (6700 cal. BP)

The CHAR analysis suggests that fires once again became significant with peak events recorded between *c.* 6700 and 3000 cal. BP (Figure 7-5a), yet the RDA indicates that the influence of fire on vegetation dynamics was at its lowest values during this period (Figure 7-6). The first *Carpinus betulus* pollen is recorded *c.* 6000 cal. BP (Figure 7.3). *Carpinus* is not a common tree in Sweden today and generally does not form pure stands but grows with other deciduous trees, particularly *Quercus* and *Fagus* (Brunet, 1997). It is confined to the southern part of the country (Hallanaro and Pylvänäinen, 2002) and does not grow in the reserve today. *Carpinus* is a shade-tolerant late immigrant to the forests of northwest Europe. It forms a dense canopy which tends to restrict shrub or herb undergrowth.

Frequent intense fires and human use of the forest (4000 cal. BP)

Some indication of limited clearance, possibly from slash-and-burn cultivation, is coincident with a slight increase in *Calluna* pollen (Figure 7-4), an indication of grazing pressure, *c.* 4000 cal. BP. Cultural indicators include continuous *Plantago lanceolata, Artemisia, Filipendula* and *Ranunculus* (Figure 7-4). A single cereal-type pollen grain *c.* 3600 cal. BP is coincident with the change in the pattern of charcoal deposition (Figures 7.3 and 7.4) and increasing values of the vegetation variance that can be attributed to fire (Figure 6). *Fagus* pollen is first recorded *c.* 4000 cal. BP at the same time as values for *Carpinus*, which is often associated with abandoned pastures in southern Sweden (Bergendorff et al, 1979), increase and *Corylus* decrease (Figure 7.3). A few tumbled down stone cairns close to the lake may well date from this time although they have not been examined in detail by archaeologists (Karin Hernborg, personal communication, June 2012).

While *Fagus* immigration is frequently associated with disturbance (Bradshaw and Lindbladh, 2005), declining *Corylus* pollen frequencies and increase in *Carpinus* are broadly synchronous within mid- to high-latitude forest ecosystems in Europe *c.* 4000 years ago (Giesecke et al, 2011). This suggests that the temporal pattern of vegetation change might be a partial response to climatic change. Many proxy records from the eastern seaboard of northern Europe show increasingly cold, moist and unstable climate at this time (Seppä et al, 2005). In Sweden, this can be associated with an increase in regionally reconstructed lake levels (Digerfeldt and Håkansson, 1993), a rise in groundwater (Hammarlund et al, 2003) and inferred hydrological changes in local bogs in Halland (De Jong et al, 2006; Gustavsson et al, 2009).

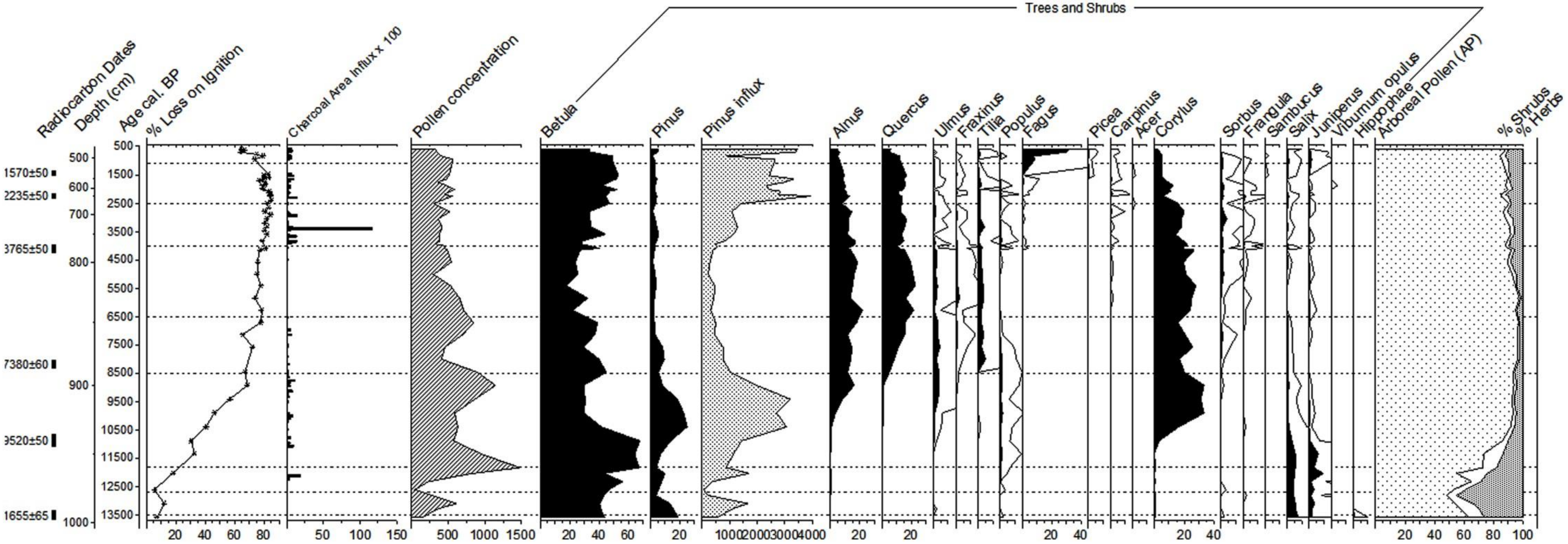


Figure 7-3: Pollen percentage diagram from Sällstorpssjön showing trees, shrubs and the AP/NAP relationship. The percentages are calculated on the sum of terrestrial pollen. Loss on ignition is the percentage weight. Loss of organics at 450. Exaggeration of select.

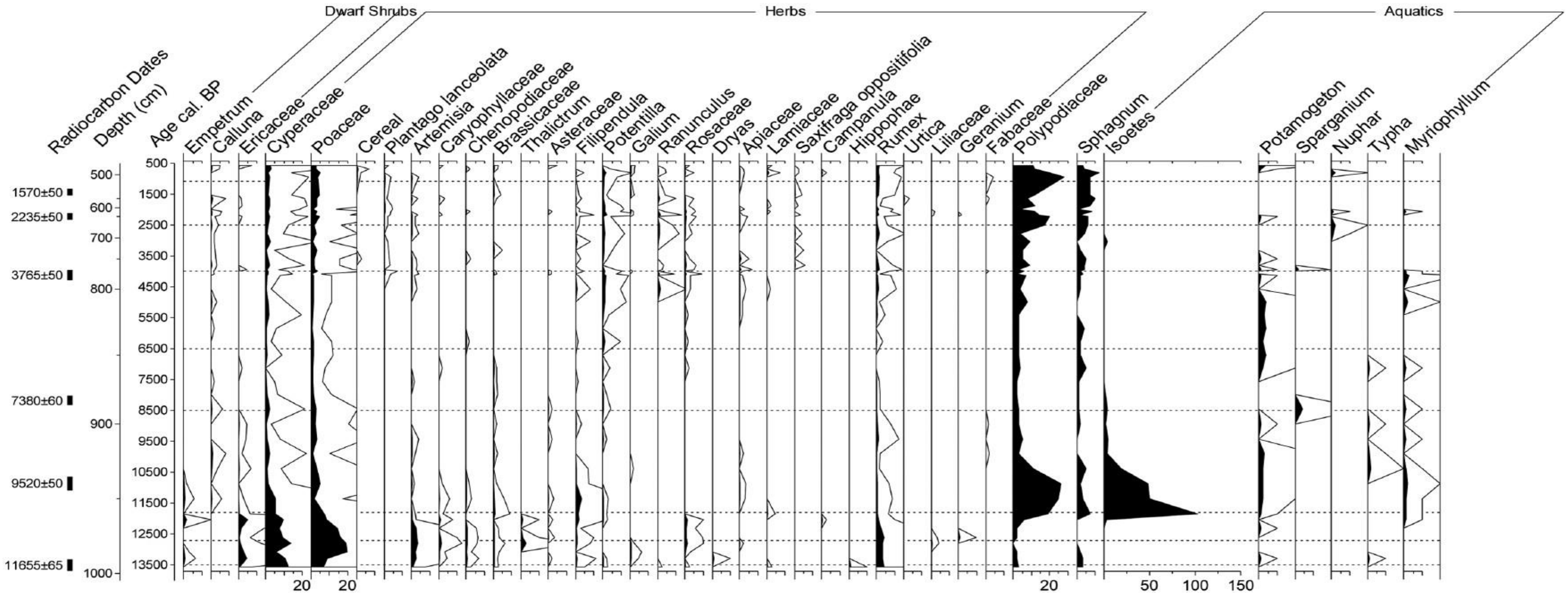


Figure 7-4; Pollen percentage diagram from Sällstorpssjön showing dwarf shrubs, herbs, and aquatics. The herb percentages are calculated on the sum of terrestrial pollen. Aquatics and Polypodiaceae, respectively. Exaggeration of selected taxa is x 10.

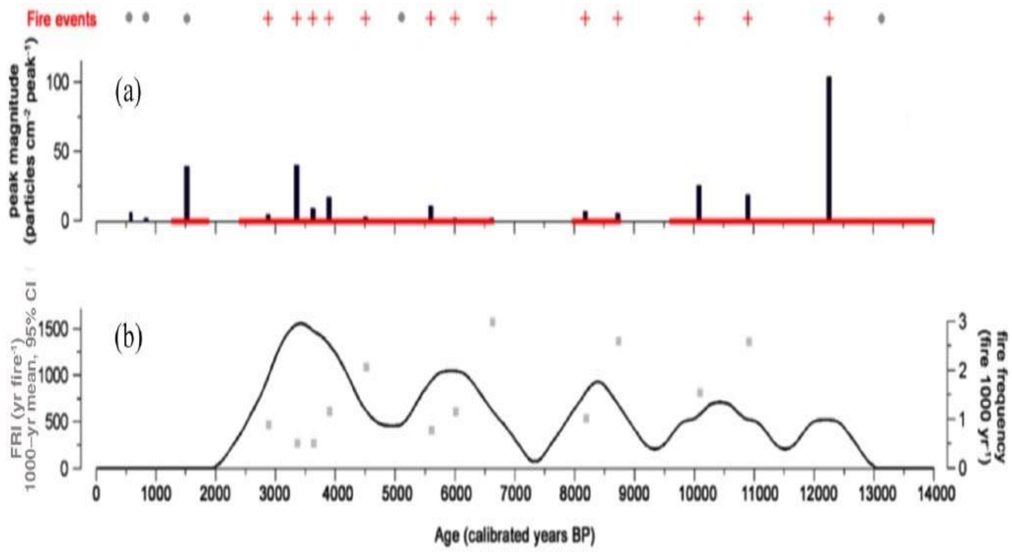


Figure 7-5: 5 (a) Reconstructed palaeofire peaks and (b) fire return interval. No sediment younger than 500 cal. BP was recovered.

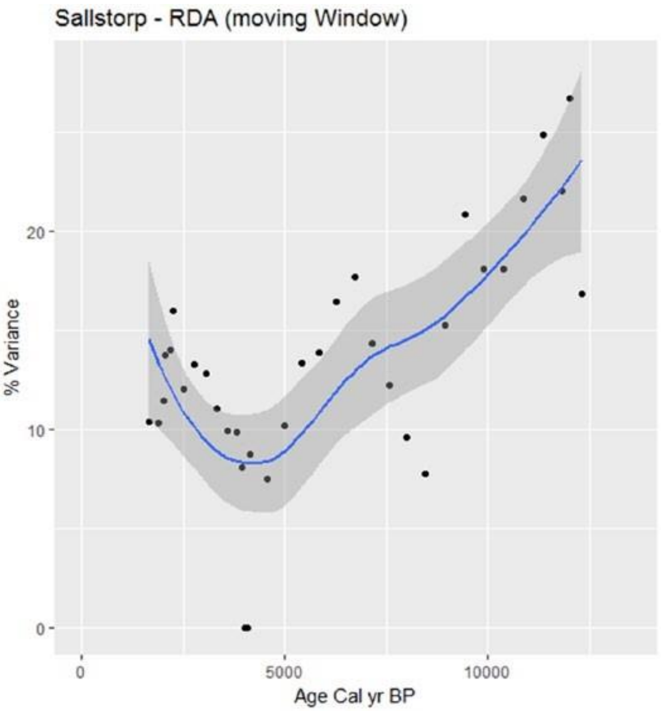


Figure 7-6: Redundancy Analysis showing the changing percentage of vegetation variance attributable to charcoal.

So, there might be underlying climatic control to the shifting nature of the vegetation composition in addition to the first weak signs of anthropogenic activity in the forest.

Many Bronze Age pollen records in south-western Sweden and Denmark (Hannon *et al*, 2008; Odgaard and Rasmussen, 2000; Sköld *et al*, 2010) show this time to be one of marked cultural impact, with deforestation and extensive vegetation alteration. At Yttra Berg, a site rich in clearance cairns and stone walls, at a similar elevation but further north and 27 km from the Halland coast, the forest is thought to have been initially used for herding or transhumance activities with microcharcoal evidence suggesting clearance by fire to benefit grazing from *c.* 4000 cal. BP (Sköld et al, 2010). On the Bjäre peninsula, a short distance south, with a very high density of well-preserved burial mounds throughout the Bronze Age, forest cover is generally estimated to be as little as 20–40%, and the mounds were probably built to be visible in an open landscape (Hannon et al, 2008). It has been argued that there was a more intense use of the landscape at that time rather than in the Iron Age because of a coastal culture and fertile soils, although in some local settings deforestation may have taken place slightly later at *c.* 3500 cal. BP (Brown et al, 2011). The few macro-charcoal sites available show Bronze Age burning was taking place on the landscape, and charcoal fragments were recovered from the base of many burial mounds (Hannon et al, 2008). Episodic burning affected many decorated Bronze Age rock carvings (Brown et al, 2011). While Bronze Age activity had a large impact on forest structure and composition over much of south-west Sweden, canopy cover and old trees may have persisted longer in upland marginal sites with poor soils such as in Almeberget Nature Reserve.

Mixed deciduous forest and wetter conditions (2500 cal. BP)

A decline in the mixed deciduous pollen communities and an increase in *Betula* can be observed during the Iron Age (Figures 7.3 and 7.4), coincident with the first major increase in *Fagus* pollen suggesting a reduction in anthropogenic use of the forest. This time is characterised by a period of rapid environmental change and cooler wetter conditions seen in many proxy records (Olsson et al, 2010). Fire peak events cease to be significant (Figure 7-5a) with a decline in fire incidence (Figure 7.3), and climatic conditions may have become unfavourable for fire, especially in these upland marginal sites. There may have been some regeneration and closing over of small glades, which *Fagus* would have been in a good position to exploit.

The residual remnants of the former mixed temperate forest are mainly around the lake (Table 7.1) and on rocky slopes which are inaccessible to grazing game. The marked increase in *Pinus* and *Picea* pollen values reflect the tree planting forestry programmes of the 19th and 20th centuries (Bradshaw et al, 2015). Otherwise, the forest reserve is today dominated by *Fagus*. The lack of charcoal in the uppermost sediments is a likely reflection of general fire suppression in Scandinavia over the last 200 years (Niklasson and Granström, 2000) and might have further facilitated the rise to dominance by *Fagus*. The RDA showed that the changing percentage of the pollen assemblage variance explained by the charcoal data declined continuously from *c.* 25% at the opening of the Holocene to a minimum value of less than 10% by 5000 cal. yr BP. This value increased during the late Holocene to almost 15% by the end of the record (Figure7- 6).

Consequences of long timescales for conservation and restoration

The late-Glacial and Holocene vegetational history of southwest Sweden shows continuous change driven by climate, a dynamic fire regime and human impact. Climatic change was most influential during the late-Glacial and the early Holocene, while human activities were the dominant drivers of forest composition during the late Holocene (Kuosmanen *et al*, 2018; Wohlfarth *et al*, 2018). At Almeberget Nature Reserve, natural fire had its greatest influence during the early Holocene, then declined in importance as a driver of vegetation change until anthropogenic burning developed during the late Holocene (Figure 7-5). What were the consequences of these changes for forest biodiversity, particularly components of the saproxylic complex? The palaeoecological record of insects, bryophytes and lichens is poor, but a record of possible diversity change could be indicated by the current host specificity of these species, which has been established for 542 red-listed saproxylic insect species in Sweden (Jonsell et al,1988) by matching the number of host-specific insects to the number of dominant/sub-dominant tree species occurring during different time periods, a clear pattern of potential diversity change through time is apparent (Figure 7-7). Red-listed insects gradually increase in diversity from the late-Glacial until 9500–6500 cal. BP when the forest had its most diverse tree flora, but was not as closed in structure as during *c.* 6500–4200 cal. BP. The subsequent increase in human impact (4200–2500 cal. BP) initially had little effect on potential insect diversity. Indeed, the slight opening of the canopy through disturbance may have favoured trees with slightly greater numbers of associated red-listed insects. Subsequently, increasing human impact was associated with continuous loss of tree and red listed insect diversity (Figure 7-7). This analysis gives an indication as to when forest conditions might have been best suited for maximum diversity of red-listed species in the past. This was the period in the mid-Holocene, when *Quercus, Corylus, Alnus, Tilia, Fraxinus, Ulmus* and *Sorbus* were the major forest trees providing far more substrate diversity for the saproxylic species than is available at present (Figure 7.3). Much surviving biological value in the reserve is linked to lichens which can switch tree hosts more easily than other species groups (Ellis, 2012; Fritz et al, 2008). All these trees still grow in the region at present but in small populations, which are severely depleted in size, and some do not grow in the *Fagus*-dominated Nature Reserve. Their reduced importance is most likely due to management history rather than significant changes in climate (Björse and Bradshaw, 1998).

Time periods	Archaeological age	Palaeoecological evidence
13,500–12,700 cal. BP		Light-demanding taxa *Juniperus, Hippophae, Empetrum*, Ericaceae, Poaceae, Cyperaceae, *Artemisia* and Chenopodiaceae on possibly unstable soils, with *Pinus, Betula, Populus* and *Salix* (Figures 3 and 4).
12,700–11,700 cal. BP	Palaeolithic 12,000–9600 BC	A decline in *Pinus* and increase in herbaceous taxa, particularly Poaceae (Figure 7-4). Organic sediment content decreases and total pollen concentration falls from 605,698 to just over 40,000 pollen/cm^3 (Figure 7.3). This is one of the few sites in Fennoscandia with a sedimentary charcoal record at this time (Clear et al, 2014).
11,700–8500 cal. BP	Mesolithic 9600–4000 BC	Tree pollen expands stepwise with Holocene warming together with a threefold increase in the percentage of organic sediment content. Fire-adapted *Pinus* has its highest values. *Ulmus* and *Alnus* values increase. The disturbance-adapted *Populus* remains an important forest component. There is a continuous charcoal record.
8500–6700 cal. BP		*Quercus, Fraxinus* and *Tilia* increase. Tree pollen diversity is high, comprising both temperate and boreal species. Low or discontinuous records of most herbaceous types and fern spores (Figure 7-4).
6700–4000 cal. BP	Neolithic 4000–1800 BC	A wide variety of deciduous trees with *Quercus, Ulmus, Tilia* and *Fraxinus* as the main dominants together with *Alnus, Betula, Salix, Sorbus* and *Frangula*. *Populus* only occasionally present. *Pinus* has declined to low frequencies. *Carpinus betulus* pollen first recorded.
4000–2500 cal. BP	Bronze Age 1800–500 BC	*Fagus* first recorded. Values for *Carpinus* increase and *Corylus* decrease towards the end of the period. Cultural indicators include continuous *Plantago lanceolata, Artemisia, Filipendula* and a single cereal grain *c.* 3600 cal. BP.
2500–1400 cal. BP	Iron Age 500 BC–AD 1100	Decrease in *Corylus* and decrease in *Ulmus* and *Alnus* frequencies. Increase in *Betula* and Polypodiaceae spores. First major increase in *Fagus* and the initial pollen evidence for *Picea*.
1400–500 cal. BP	Medieval AD 1100–1500	Decline of mixed deciduous taxa and rise to dominance of *Fagus. Ulmus, Fraxinus, Corylus, Sorbus* and latterly *Quercus* decrease. Poaceae and Cyperaceae values maintained with *Rumex acetosa, Galium*-type, *Filipendula* and low cereal pollen values. A subsequent peak in Polypodiaceae spores is followed by successions involving *Juniperus* and *Salix* and increasing *Fagus* frequencies as cultivation is abandoned.

Table 7.7. Summary of palaeoecological dynamics in Almeberget Nature Reserve.

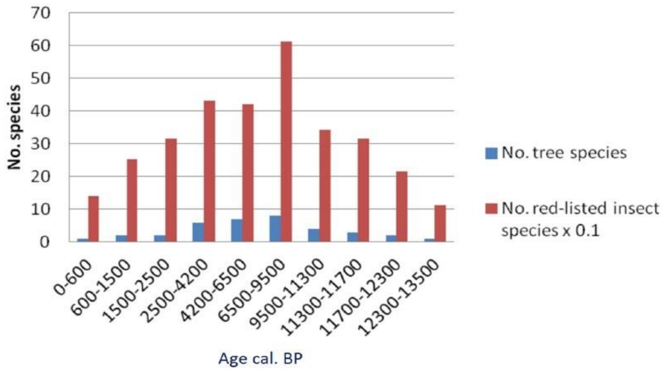


Figure 7-7: The number of red-listed saproxylic insects (red) associated with specific dominant and sub-dominant tree species (blue) at Almeberget Nature Reserve.

7.5 Conclusion

The record of human–nature interactions with the environment goes back much further than we often believe. A dynamic equilibrium exists where there is not a single climax or a single reference but a range of variability within which there are systems driven by dynamic combinations of natural and anthropogenic disturbance. During the early to mid-Holocene, more species-rich forest composition existed within the constraints imposed by climate in southern Sweden. Human use of the forest has resulted in significant shifts in canopy dominants, even in this Nature Reserve where anthropogenic influence has been low impact. When fire regimes have been periodically severe, the disturbance has exerted a considerable impact on forest composition and structure. Suppression of fire, as is documented in southern Sweden over the last 200 years (Bradshaw et al, 2010), along with the national planting programmes of the 20th century have assisted *Fagus* and *Picea* to obtain canopy dominance.

Nature reserve planning in Swedish forests is often species driven, based on which red-listed species live on the major stand dominants today (Fritz, 2009). The evidence from the paleoecological record shows that many forests have undergone structural and compositional changes (Björse and Bradshaw, 1998). Forests are not steady-state systems, so knowledge of the range of variability over long timescales is valuable for the future. Appropriate management goals might usefully combine preservation of existing diversity with restoration of former diversity, guided by the palaeoecological record. An appropriate restoration goal might be to encourage the spread of mixed deciduous trees and their associated fauna and flora. Diverse forest systems are more resilient to unanticipated impacts and reduce risk of biodiversity loss. This forest 'hotspot', in contrast to the surrounding landscape, can claim to have unbroken forest continuity throughout the Holocene, albeit with constantly changing structure and composition and some disturbance. A similar conclusion was reached by Lindbladh et al. (2008) and Bradshaw et al. (2015) based on data from four small hollows all located close to the study site. Taken together, these analyses support our initial hypothesis. The most likely reason for the rich epiphytes, wood-inhabiting fungi and invertebrate communities so valued today is that forest continuity has been maintained despite significant tree composition dynamics. There has been anthropogenic impact but less than that recorded from the more heavily utilized coastal environments or nearby sites such as Yttra Berg (Sköld et al, 2010). The relatively low-intensity anthropogenic disturbance that Almeberget Nature Reserve has had in the past may well be a feature critical to maintain its biodiversity in the future.

Chapter 8 Quantifying the impact of fire events on Holocene vegetation dynamics in Europe

8.1 Abstract

Fire events and subsequent fire regimes are intrinsic within Holocene vegetation dynamics across Europe. Quantifying this effect can be achieved using charcoal fragments (proxy for fire events) as a constraining variable in redundancy analysis with vegetation dynamics as the response variable. Here, the results of charcoal analysis and palynology for Robinsons Moss, Peak District are compared with three European sites in Germany, Denmark and Sweden. The results show that the percentage of variance in vegetation dynamics explained by fire events for the last 13,500 years at these sites is below 30%. This implies that fire is not the dominant driver over this time period. Maximum levels of impact occur during the Mesolithic period and for the last millennia. The lowest percentage in the variance occurs at Gribskov, Denmark (7 – 5%) from 5000 – 2000 years BP. This site is relatively isolated from human activity, whereas the highest percentage occurs at Carlshof, Germany (30%) situated close to areas of historic human habitation. A general decrease in the impact of fire on the vegetation dynamics is seen from 6000 years BP to 2000 years BP with an increase occurring from 2000 years BP to the present day. Although there are local influences on fire events, the overall indication is that these ecosystems are driven long-term by climatic conditions.

8.2 Introduction

The role of fire within vegetation dynamics is difficult to disentangle from changes in climatic conditions as fire-vegetation relationships are usually non-linear (Whitlock, 2010) and include feedback mechanisms (Cochrane, 1999). Palaeoecological studies can provide insights into the long-term impact of various disturbances on vegetation dynamics however, they are difficult to untangle from a complex system of environmental conditions and feedback mechanisms (Fyfe *et al*, 2018; Hawthorne *et al*, 2016; Blarquez, *et al,* 2015; Marquoy *et al*, 2002). Previous chapters have discussed the impact of fire events on vegetation dynamics and the influence of climatic conditions at several sites across the Peak District. A probable pattern of wet/dry shifts was identified using geochemical and fungal spore analysis (chapters five and six) that was linked to episodic fire events. Chapter six showed that the percentage of variance in the vegetation dynamics explained by fire (microcharcoal fragments) for sites within the Peak District and surrounding areas did not exceed 30%. Here RDA analysis for Robinsons Moss is compared with RDA analysis for Gribskov (Denmark), Carlshof (Germany) and Sällstorpssjön (Sweden), (Overballe-Petersen *et al*, 2012; Bradley *et al*, 2013; Hannon *et al*, 2018 respectively) using macrocharcoal fragments to represent fire events. The pollen percentage data will contain both local and regional pollen records so the RDA percentages may be lower than if only local pollen was used in the analysis (Colombaroli *et al*, 2018). The charcoal analysis and palynology results for these European sites are already published (apart from Robinsons Moss), however apart from Sällstorpssjön, redundancy analysis (RDA) has not previously been explored in these published papers. Redundancy analysis is a linear method which assesses the linear relationship between the response variable (pollen percentages) explained by (redundant with) charcoal fragments. RDA provides a first constrained axis and *n* unconstrained axes (“PCA”). This provides a technique for assessing the extent to which vegetation change (pollen percentage data) is explained by fire (charcoal fragment data) without the influence of sedimentation rate as both the charcoal record and the vegetation dynamics will be subject to sediment accumulation rate change. Species – fire relationships can change over time, so a moving window approach is used to determine if fire is more important for vegetation changes during different millennia, for example mid Holocene and late Holocene. Use of this technique can be seen in Colombaroli (2018) which uses RDA to describe temporal changes in vegetation dynamics explained by different drivers for the regions surrounding Lake Simbi, Kenya.

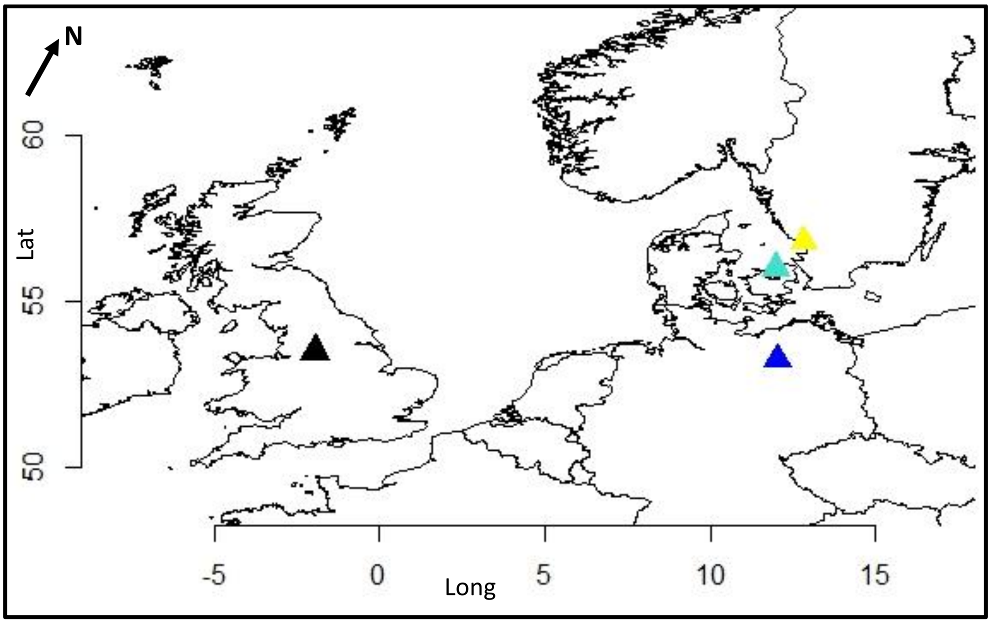


Figure 8-1: Site map for Robinsons Moss, U.K. (black triangle), Sällstorpssjön, SW Sweden (yellow triangle), Gribskov, Denmark (turquoise triangle), Carlshof, Germany (blue triangle). (R development team, 2008).

The sites used in this study are a mixture of forest hollows (Gribskov and Carlshof), a kettle hole lake (Sällstorpssjön) and a blanket bog (Robinsons Moss). Although there are differences in the types of sedimentary deposits, the core extraction sites lie in a similar climatic zone (temperate oceanic) and are within a narrow longitudinal range from 53.25 to 56.51 N. The sites represent a temporal range from 13,500 years BP to present day (figure 8-1).

8.3 Materials and methods

8.3.1 Pollen analysis

Descriptions of the pollen analysis method for the sites used in this chapter can be found in the relevant published papers for Gribskov, Carlshof and Sällstorpssjön (table 8-1). Pollen analysis method for Robinsons Moss can be found in Chapter five.

8.3.2 Charcoal analysis

Descriptions of the charcoal fragment analysis method for the sites used in this chapter can be found in the relevant published papers for Gribskov, Carlshof and Sällstorpssjön (table 8-1). Charcoal analysis method for Robinsons Moss can be found in Chapter five.

Site name	Easting	Northing	Elevation a.s.l	author	dates yrs BP	site type	charcoal
Robinsons Moss (RM), U.K.	5348220	1941878	500	unpublished	0 – 8200	blanket peat	microscopic
Sällstorpssjön (S), S. Sweden	1253275	5651175	150	Hannon *et al*, 2018	2233 – 13500	kettle hole lake	microscopic
Gribskov (G), Denmark	56027047	1234099	44	Overballe-Peterson *et al*, 2012	2955 – 10830	forest hollow	microscopic
Carlshof (C), Germany	5325000	1304000	80	Bradley *et al*, 2013	2727 – 10000	forest hollow	microscopic

Table 8-1: Meta data for sites used in European analysis

8.3.3 Age depth models

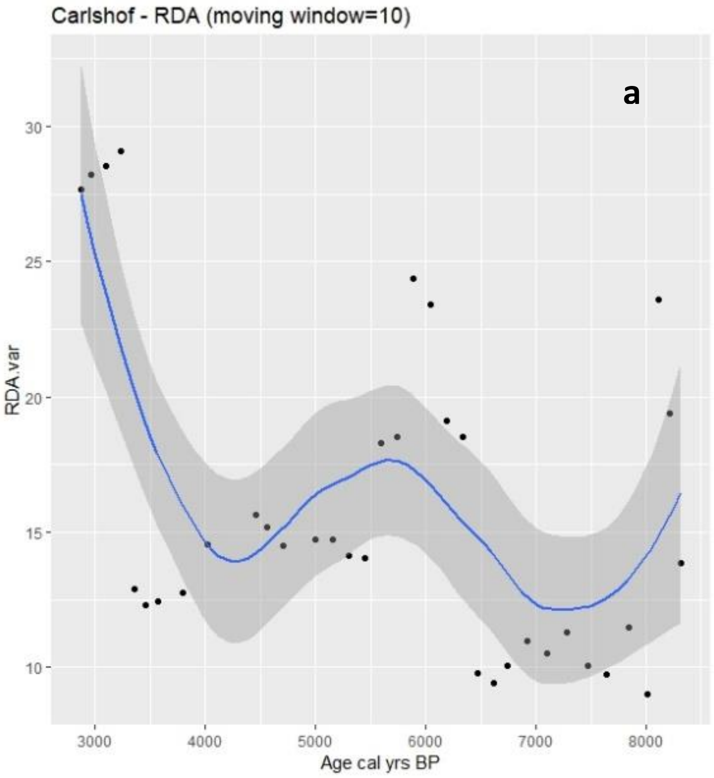
The depth-age models for Gribskov, Carlshof and Sällstorpssjön can be found in the published papers. The age-depth model for Robinsons Moss can be found in Chapter five.

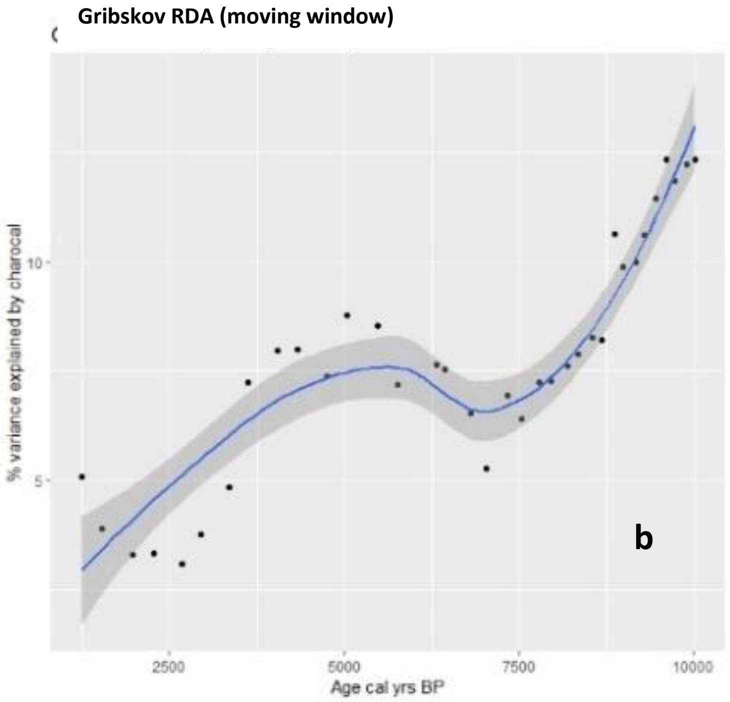
8.4 Quantitative analysis

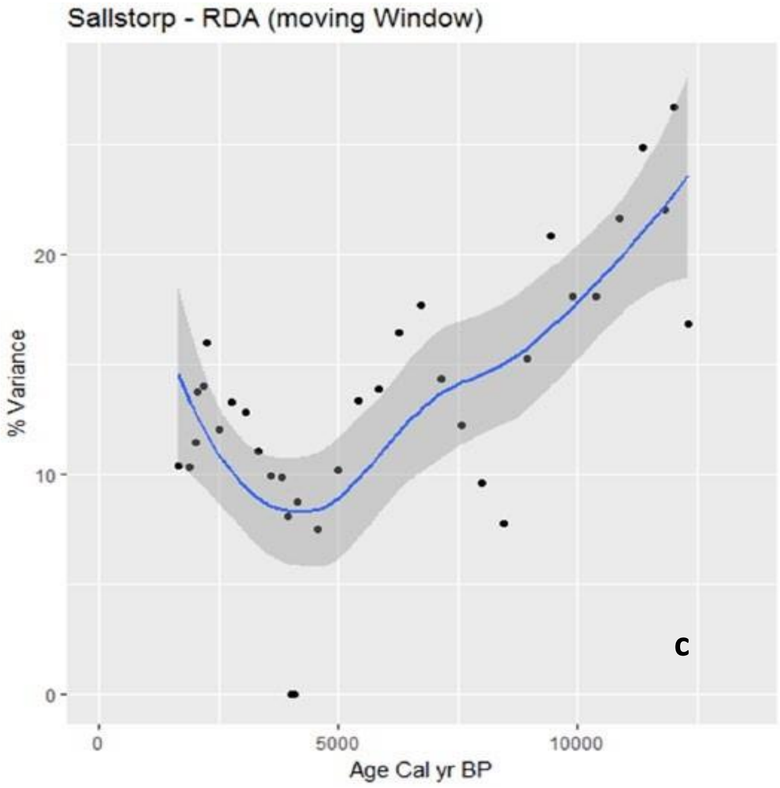
The following method for redundancy analysis is adapted from Colombaroli (2018). To understand the impact of fire on vegetation dynamics, macroscopic charcoal fragment flux was used as the explanatory variable and pollen percentages as the response variable. An indirect gradient analysis was estimated using a detrended correspondence analysis (DCA with percentage data, detrended by segment and no rare taxa down weighted) to extract underlying gradients in the pollen percentage data. Principal Component Analyses (PCA) were used as the data were unimodal, DCA axis 1 < 2 SD (Colombaroli *et al*, 2009; Ter Braak & Prentice, 2004). Redundancy Analysis was then used to determine a quantitative estimate for the percentage of variance in the vegetation explained by fire. A 10 sample moving window approach was used to extract the variance at each iteration. All calculations were carried out in R (R Development Team, 2008).

8.5 Results

The sites used in this study vary. Sällstorpssjön is a kettle hole lake in a forest at 65 m a.s.l.; Carlshof is a small forest hollow surrounded by *Fagus* and *Pinus* forest; Gribskov is a deep peat area in a forested region (*Picea* and *Fagus*) and although there is a historic heavy human influence, the area was abandoned 300 years ago; Robinsons Moss is an ombrotrophic mire at 500 m a.s.l. surrounded by *Calluna* vulgaris with trees such as *Betula, Alnus and Sorbus* on the lower slopes. Despite differences in altitude, ecology and other parameters, there are trends in how the ecosystems respond to fire events during the Holocene. Below are the plots of RDA values with age years BP for the four sites.




Gribskov RDA (moving window)
% variance explained by charocal
10
5
2500
5000
7500
10000
Age cal yrs BP
b


Sallstorp - RDA (moving Window)
% Variance
20
10
0
0
5000
10000
Age Cal yr BP
c

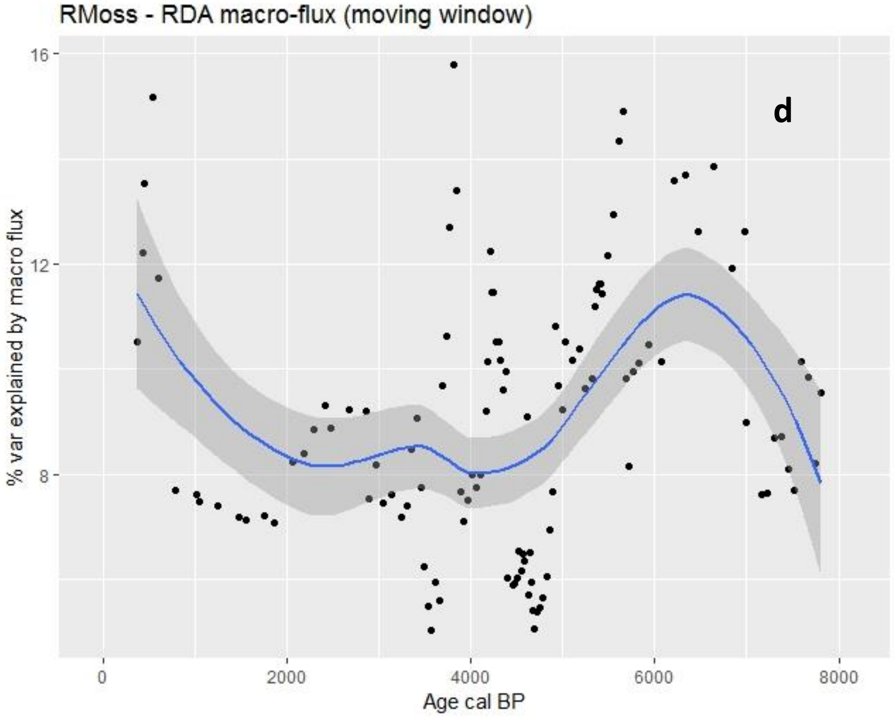
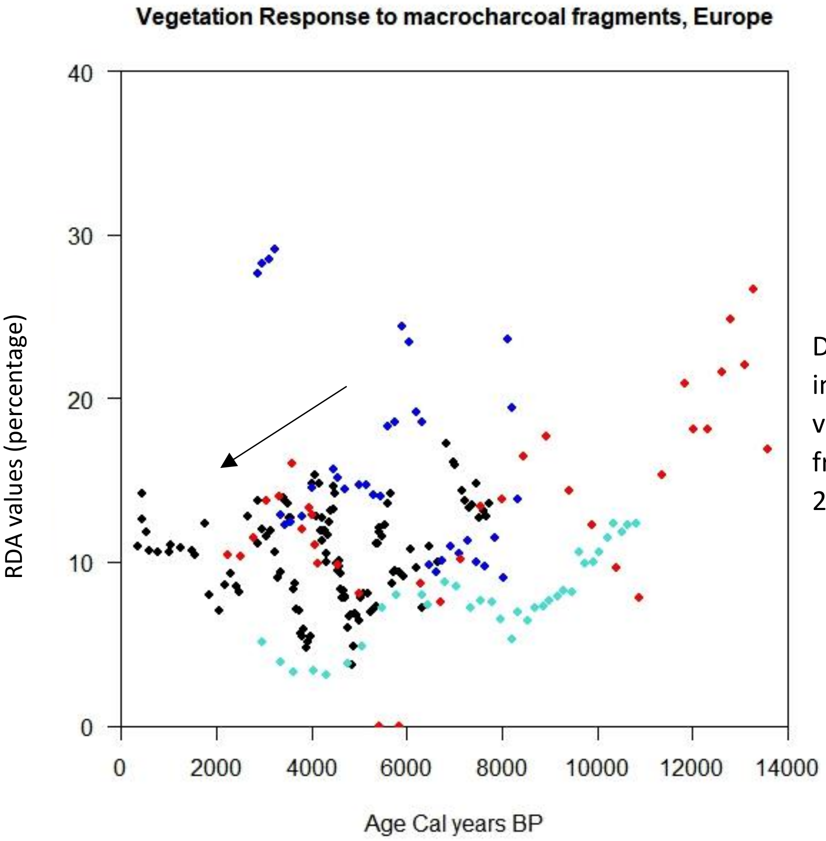


Figure 8-2: Redundancy analysis (RDA) showing the percentage of variance (inferred by pollen percentages) explained by fire (inferred by macroscopic charcoal fragment quantities) for Carlshof, (a), Gribskov (b), Sällstorpssjön (c), Robinsons Moss (d) plotted against age cal yrs BP. Points represent RDA values using a moving window (10), blue line obtained using a loess smoothing function (span = 0.3), and shaded areas represent 95% confidence limits.

Age yrs BP	RM	S	G	C
1000 - 0	11.81	na	na	na
2000-1000	10.58	10.73	na	na
4000-2000	9.45	12.06	5.20	14.9
6000-4000	10.02	7.66	5.38	16.24
8000-6000	12.93	14.06	7.70	12.86
10000 - 12000	na	15.51	na	8.23
12000-10000	na	19.85	na	na
14000-12000	na	22.60	na	na

Table 8-2: Mean RDA values (describing the percentage variance in vegetation dynamics explained by fire events) for Robinsons Moss (RM), Sällstorpssjön (S), Gribskov (G), Carlshof (C) calculated using 2000 year bins prior to 2000 years BP and in 1000 year bins for 2000 – present day.

In table 8-2, Binned RDA percentage values for three of the sites, Robinsons Moss, Sällstorpssjön and Gribskov show a decreasing trend from 8000 to 2000 years BP. Carlshof shows an increasing trend.



Decreasing trend for impact of fire on vegetation dynamics from 5000 years BP to 2000 years BP

Figure 8-3: Scatter plot of RDA values (vegetation response to fire events with macrocharcoal fragments) for Robinsons Moss (black), Carlshof (blue), Sällstorpssjön (red), Gribskov (turquoise) plotted against age Cal years BP.

Figure 8-2 shows that fire events have a higher impact 13500 - 7000 years BP as shown in the results for Sällstorpssjön and Gribskov where values show an increasing trend from ~ 20% up to ~ 30 % during this time. Higher values are seen for Robinsons Moss during the Mesolithic period from 8000 – 7000 years BP. At Robinsons Moss, the percentage values fluctuate between 7000 years BP to around 2000 years BP. There is a general decreasing trend for the impact of fire on vegetation dynamics from 5000 years BP to around 2000 years BP (figure 8-3). The percentage value for this impact is mostly below 20 % for Robinsons Moss, Gribskov and Sällstorpssjön although some values at Carlshof are between 25 and 30 %. All of the sites show that fire has a reduced impact on vegetation between 4000 – 2000 years BP. Robinsons Moss shows that fire has a higher impact on the vegetation during the last 1000 years.

8.6 Discussion

The data in this study derives from a small number of sites, so only tentative interpretation can be drawn. However, the same method is used for charcoal analysis at all of the sites and by using RDA analysis, charcoal and pollen data are compared for each site and then RDA values are compared between sites, so data transformation is not necessary. Despite the small number of sites, some general trends can be seen in the data (figure 8-3).

Although there is a difference in the types of sedimentary deposit, there is a consistency in the percentage of variance in the vegetation dynamics explained by fire for these sites although values at Carlshof are higher than at the other three sites. The extraction site at Carlshof is a forest hollow within a deciduous forest in a low lying region of Germany, in close proximity to areas of historic human habitation, so it would make sense for fire events to have a higher level of impact on vegetation dynamics than the other sites that are at more remote locations.

The temporal fluctuations in the RDA values reflect the quantity of biomass available to burn. Fire events are dependent on suitable conditions for fire to occur, which is a product of long-term and short-term climatic conditions. The moving window technique adjusts for temporal differences in species relationships with fire events (Colombaroli *et al*, 2018) so is a useful tool to show temporal changes in the occurrence of fire events. The general trend for all of the sites here is that fire at 30% does not explain the majority of the variation in the vegetation dynamics, but it is an important factor. The fluctuations in the impact of fire events will reflect differences in local conditions and the influence of other disturbances to the ecosystems such as human activity and local climatic conditions and natural disturbances such as wind throw and lightning. This is also seen in a study by Colombaroli *et al* (2018) which looks at fire in savannah grasslands around Lake Simbi, Kenya. Here the percentage variance is below 30 %. A previous paper investigating Holocene fire in the Swiss Alps recorded a maximum RDA value of 32.2 % (Colombaroli *et al*, 2009).

There are some differences in the response at each site. At Gribskov (Denmark), figure 8-2 and table 8.2 show a decreasing trend for the time period 7000 – 4000 years BP, Overballe-Petersen (2012) suggests either changing climatic conditions or change in forest management as the cause of a lack of fire events (Overballe-Petersen *et al*, 2012). The impact shown for this time is 5.38 %. Hannon *et al* (2018), in their paper for Sällstorpssjön in SW Sweden, describes a change to wetter climate conditions also during this time, this is generally thought to reflect a deterioration in climate conditions. All of the sites show a reduction in the percentage values but at different time periods during the mid Holocene. At Robinsons Moss, the temporal percentage values for vegetation changes explained by fire reduces until around 5000 years BP and increase thereafter. At Carlshof, the reduction occurs earlier around 7000 years BP. Harrison *et al* (1996) used lake level records to determine paleoclimates in northern Eurasia. In his paper, from 7000 years BP lake levels were thought to be higher due to an increase in summer rainfall, i.e. wetter conditions during the growing season. This coincides with an expansion of forest species across Europe. Harrison *et al* (1996) then describes a return to drier conditions in the mid – late Holocene, so it would seem that fire is driven by changes in climatic conditions certainly during mid Holocene at these sites, but these changes occurred at different time periods due to differences in local conditions. The temperature record compiled by Langdon *et al* (2004) using chironomid assemblages, also shows fluctuating temperatures during the mid to late Holocene. This record shows a reduction in temperature between 6000 – 5000 years BP and an increase thereafter. All of the sites seem to be driven by changes in climatic conditions until around 2000 years BP when fire increases in line with periods of human expansion such as the Bronze and Iron Ages (not seen at the Denmark site). A reduction in the percentage values is seen between 2000 – 1500 years BP consistent with climatic deterioration across Europe at this time (Oldfield, 2005; Simmons, 2003; Bradshaw & Sykes, 2014).

The data record for Sällstorpssjön record starts post 2000 years BP, however fire suppression can be seen in many palaeoecological records for Sweden for this recent history (Clear *et al*, 2013, 2015). In this study, the increase seen at Robinsons Moss during the last 2000 years is not seen in the record for, Gribskov, Denmark. Certainly over the last few hundred years farming land was abandoned here with the implication that the area would be less subject to management by fire during this time. No further explanation is available for this reduction in the impact of fire events at Gribskov (Overballe-Petersen *et al*, 2012).

8.7 Conclusions

The vegetation dynamics at the four sites are more likely to be driven by changes in climatic conditions than fire events. A maximum of 30% of the variance in vegetation dynamics is explained by fire across this region. This is consistent with other studies in Europe for example Colombaroli *et al* (2018, 2010) and show that fire, although not the main driver, contributes an important impact on overall vegetation dynamics.

Peaks in the percentage explained by fire is seen between 8000 and 7000 years BP which coincides with conditions drier than present (Harrison, 1996).

Chapter 9 General Discussion and conclusions

9.1 Discussion

The main aim for this thesis was to use image analysis of charcoal fragments to investigate how and why charcoal fragment quantities varied across northern England and northern Europe in answer to the following questions:-

1. Can a semi-automated image analysis system generate a reliable estimate of charcoal frequencies in sediments?
2. How does the Holocene fire regime at Robinsons Moss, Peak District compare with the regional fire regime across the Peak District?
3. How important has Holocene fire been as a driver of vegetational dynamics in northern Europe?

This Chapter will discuss the achievements that this thesis has made in answer to these questions.

The overall aim of the thesis has important implications for the management of ecosystems where fire has an historic and contemporary presence. This concept applies equally to Boreal forests, *Calluna* peat ecosystems and others where dry biomass is likely to accumulate. Here fire-vegetation-climate relationships for various examples of these types of systems have been explored. Charcoal fragments found in Holocene sedimentary deposits are produced in the absence of oxygen when organic material burns. The relationship between organic material and ignition source is driven by a myriad of factors but exhibits temporal and spatial patterns that allow an understanding of this relationship to develop. Such studies however rely on robust methodologies and statistical analysis to provide meaningful interpretations. Chapter three describes a detailed method for the analysis of macrocharcoal that can be used for all types of sediment. Although methods used to quantify macroscopic charcoal have similarities, the choice of method and quantification can produce different results as shown in Chapter six, a published paper that highlights the differences and similarities between two common methods; quantification using image analysis and quantification using a mass method. This paper also showed that different results can be produced depending on the choice of extraction site within a peat bog i.e. near the edge or in the centre of the peat bog (Halsall *et al*, 2018). These results indicate the importance of a standardised method for the analysis of charcoal fragments and consideration of the position of the extraction site within a mire system. A further issue that has been discussed is the size of charcoal fragments included in the analysis. There is not a standard size that determines whether a fragment is from a local or a regional fire. This is partly due to the uniqueness of individual fire events in terms of temperature, crown or ground fire, distance from the fire event to the extraction site, taphonomic differences and differences due to the type of burnt plant material and other factors that make interpretation of charcoal fragments difficult. Some studies have shown that temporal changes in charcoal fragment quantities and fire return intervals can provide sufficient information to describe and interpret a fire regime for a locality (Carcaillet *et al*, 2007). Uncertainties can arise when quantities of charcoal fragments are interpreted in more detail such as indicating the severity of fire events and the distance of the fire from the extraction site. These uncertainties are difficult to resolve as charcoal fragments found in sediments can vary widely in size from less than 50 microns to greater than 2 mm. Figure 5.16 shows that the impact of microcharcoal (>50 µm on pollen slides) and macrocharcoal (> 180 µm length fragments) is very similar apart from the effect of a fire ~ 7300 years BP that created a higher peak in macroscopic fragments compared to microscopic fragments.

There is some evidence that the type of vegetation burnt can be analysed if charcoal fragments are quantified as deriving from broad categories such as woody material, herbaceous or grass material (Umbanhower & McGrath, 1998; Enache & Cumming, 2006) and also that the length / width ratio (L/W) may be useful as an indicator of the type of vegetation burnt (Jensen *et al*, 2007; Finsinger, 2014). Some analysis using these categories was completed for Robinsons Moss and is shown in chapter three and in figure 5-31. Charcoal fragment quantities vary due to differences in the general parameters of fire events and differences in the transportation, deposition and fragmentation of the charcoal fragments. Empirical research such as Clark (1988a, b) explored the theory of particle motion, however this has continued to be challenged in reference to charcoal particles as they can also be transported through water as well as through air. Figure 5-16 showed that for peat bog sites, the impact of larger particles and smaller microscopic particles can impact vegetation dynamics to a similar extent. Adolf *et al* (2017) found that both microcharcoal and macrocharcoal described regional fire.

Charcoal fragments vary in quantity across a site (Halsall, 2018) however, quantities and sizes of fragments can vary depending on the choice of method for processing and quantification of fragments. Carcaillet *et al* (2001) showed that this effect can be minimised by the processing of at least 1cm^3 of sediment or up to 3cm^3 if there is a high sedimentation rate. Although the effect on the vegetation can be similar, microscopic charcoal found on pollen slides (< 50 microns) presents a different fire regime to the macroscopic charcoal fragments (> 180 microns) produced from a sieving method as shown in the various Tilia diagrams in chapter five and in the correlation of charcoal fragments with specific taxa. This complex mix of method and taphonomy can make interpretation of charcoal fragments difficult. So that similar parameters are measured, chapter four used the fire regime derived from microcharcoal (found on pollen slides) for Robinsons Moss and compared the results with other sites from northern England which also use microcharcoal. Chapter eight discusses the fire regime derived from macrocharcoal fragments for Robinsons Moss and three other sites in Europe. The results showed that there are trends in the response of the vegetation to fire events which implies that climate is driving the ecosystems.

For the sites used in this analysis across the Peak District (see table 6-2), the implication is that microcharcoal has a greater impact on the regional pollen percentages, which indicates that microcharcoal, having a greater connection with regional vegetation is more likely to have a similar source area to pollen and that the source area for microcharcoal is wider. For Robinsons Moss, macrocharcoal has a greater impact on the vegetation between 8,000 - 6000 years BP however, microcharcoal showed a greater impact on the vegetation than macrocharcoal between 5000 - 4000 years BP, so there are clearly some differences in the fire regimes that these different sizes describe. If the differences in charcoal source area is correctly surmised, then this would imply that fire was more wide spread between 5000 – 4000 years BP and during the last two millennia and that it was more localised during the early Mesolithic period (8000 – 7000 years BP). Alternatively, the difference in impact of macrocharcoal from 10,000 – 7,000 years BP and from 5000 years BP to the present day shown in figure 8-3, could indicate a difference in the type of vegetation being burnt. The early time period was more forested as shown in Woodbridge *et al* (2014). Figure 6-1 shows that half of the earlier forest cover for the U.K. was lost by 6700 – 5500 years BP (Roberts *et al*, 2018; www.nature.com/scientificreports), so the greater impact of larger macrocharcoal during the earlier time period could indicate a closer association with tree taxa dynamics whereas the smaller fragments could have a greater association with shrub/ grass fires during the last five millennia. *Calluna vulgaris* was more wide spread in northern England from 5000 years BP (Fyfe *et al*, 2018).

Despite the issues in analysing charcoal fragments raised in the preceding paragraphs, meaningful interpretation of fire regimes has been achieved in many research projects across the globe. The new Holocene fire record produced as part of this project was extracted from peat sediment at Robinsons Moss in the Peak District. As expected, this record showed temporal differences in charcoal fragment quantities. To interpret this record in terms of the fire-vegetation-climate relationships, other botanical proxies were also quantified. This has been described in Chapter five. Fungal spore analysis has been shown to add important hydrological information similar to other studies such as Innes *et al* (2010), Yeloff *et al* (2007) and Blackford *et al* (2006). Robinsons Moss has been shown to be a natural climatically driven ombrotrophic mire ecosystem. Although fire events have occurred throughout its history since peat initiation around 9000 years ago, fire has not had a consistent impact on the vegetation dynamics. The impact has varied in the percentage of the variance in the vegetation dynamics explained by fire from 5% to around 16% for Robinsons Moss and up to 26% for the Peak District area. This relatively low value indicates that climate is more likely to have driven the vegetation dynamics than fire events in the long-term although local conditions contribute to variation in the response of vegetation assemblages seen in local studies. So charcoal fragments have varied in quantity as a response to climatic conditions impacting on the vegetation. The low impact of fire on vegetation assemblages is confirmed in the lack of statistical significance of many individual taxa with fire events seen in Chapter five. Fire events have been shown to impact on soil chemistry. Fire events can also be a significant factor in the *Calluna* / Poaceae relationship on peat systems (Davies, 2016). The charcoal fragment quantities vary at Robinsons Moss depending on the prevailing climatic conditions leading to a build-up of suitable biomass and dry conditions suitable for ignition. Fire events could also have been used by Mesolithic people to manage the forest present on Robinsons Moss during the drier climatic conditions of the early Holocene, which has resulted in localised impacts on the vegetation. This interpretation has been corroborated with reconstruction of the vegetation dynamics and interpretation of the fire regime for the area surrounding Robinsons Moss discussed in Chapter six and also in Chapter eight where Robinsons Moss is compared with three other sites in Europe.

Chapter seven is a published paper that explores the fire-vegetation-climate relationship during the Holocene for a nature reserve in southern Sweden. Here, fire also impacts on the vegetation, with peaks in charcoal fragments being interpreted as both human ignited fire events and natural fire events during ameliorated climatic conditions similar to those that occur at Robinsons Moss. For example, both areas show an increase in fire events during the Bronze Age (4500 – 2800 years BP in the U.K.). This paper explores the significance of fire events in relation to biodiversity and found that a combination of low intensity fire events with a mixed deciduous forest was the time period with the highest level of biodiversity. The species response analysis found that the impact of fire on the vegetation dynamics varied between 10% at around 5000 years BP and 25% during the recent millennia. The increase during recent millennia is also consistent with results from Robinsons Moss. Although this site has experienced low anthropogenic activity, fire has had a relatively consistent influence. Fire events increased when *Pinus* was dominant and decreased as deciduous trees increased. This site, in common with other sites, in this thesis shows the complexities inherent within fire – vegetation – climate relationships. It has also shown the low influence of fire on vegetation dynamics in common with other sites in this study.

Fires that occur during the Holocene, from 10,700 years BP to the present day are a relevant source of information in our pursuit to understand what could happen under future scenarios for U.K. upland peat ecosystems of increased summer temperatures and reduced precipitation. The U.K. is one of the globally rare geographical locations where climatic conditions are suitable for peat sediment to accumulate. However, this could change over the next century and peat deposits that are currently carbon deposits could switch to carbon sources if wildfires increase, leading to even further increases in atmospheric $C0_2$ levels (Gallego-Sala *et al*, 2016; Flannigan *et al*, 2009; Ellis *et al*, 2001).

In answer to the research questions that have been investigated for this study, namely how and why do charcoal fragments vary during the Holocene, this thesis has shown that fire events, although unique, are intrinsically interwoven with climatic conditions. Fire has also been (and continues to be) a management tool to control ecosystems. These changes subsequently feedback into climatic conditions. This is a modern management tool but has also been used by people during earlier millennia. During the early time periods, the ecosystems have been shown to have remained mainly under the control of climatic conditions, but this cannot be said to be the case for more recent time periods, when temporally earlier fluctuations are replaced with a steady increase in fire events. Ultimately, although there will always be a desire by humanity to control and manage ecosystems such as upland peat habitats, we should remember that how an ecosystem responds to any changes we make, can be seen in both the short term over a few years and also over much longer time series. It is important that we continue to study these long-term environmental responses to factors such as fire so that we can understand and mitigate against any long-term climatic changes that could impact on short-term management plans.

9.2 Conclusions

Charcoal fragments can be analysed successfully using image analysis as described in this thesis. This method can be used to distinguish between shapes and size of charcoal fragments that can add further detail to analysis of the type of vegetation burnt in fire events.

For Robinsons Moss, charcoal fragments vary depending on the vegetation response to climatic conditions. Taxa such as *Calluna vulgaris* and *Quercus* probably represent the type of vegetation that is being burnt at Robinsons Moss.

Regionally, charcoal fragment quantities vary due to changes in vegetation as a response to changes in climatic conditions.

Across northern Europe, climatic conditions probably drive the occurrence of episodic fire events.

9.3 Further work

Redundancy analysis has proved to be a useful technique in developing a more detailed understanding of fire – vegetation – climate relationships as it compares episodic fire events with vegetation dynamics at each site and then compares the RDA values across regions and continents. This means that fire at each site is analysed irrespective of differences in sediment accumulation rates. Further work in analysing more fire records using this technique would be useful in developing our understanding of fire across landscapes.

The lack of a standardised method for the analysis of charcoal fragments, presents difficulties in the comparison of fire regimes that use different methods. A method using image analysis in combination with free software is presented in this thesis which could be employed as a standardised method. Using the same method for data compilation studies would improve the statistical robustness of interpretation of fire regimes; sensitivity in data is more likely to be retained. This can be lost when transformation statistics are employed to standardise charcoal fragment values. Further work could be done to determine the volume of sediment that is optimum for analysis of the different type of sediments e.g. peat, lacustrine and forest hollow.

“ The last ever dolphin message was misinterpreted as a surprisingly sophisticated attempt to do a double-backwards-somersault through a hoop whilst whistling the ‘Star Spangled Banner’, but in fact the message was this: *so long and thanks for all the fish”*

Douglas Adams. The Hitchhiker’s Guide to the Galaxy

We ‘manage’ ecosystems without truly understanding the long term consequences

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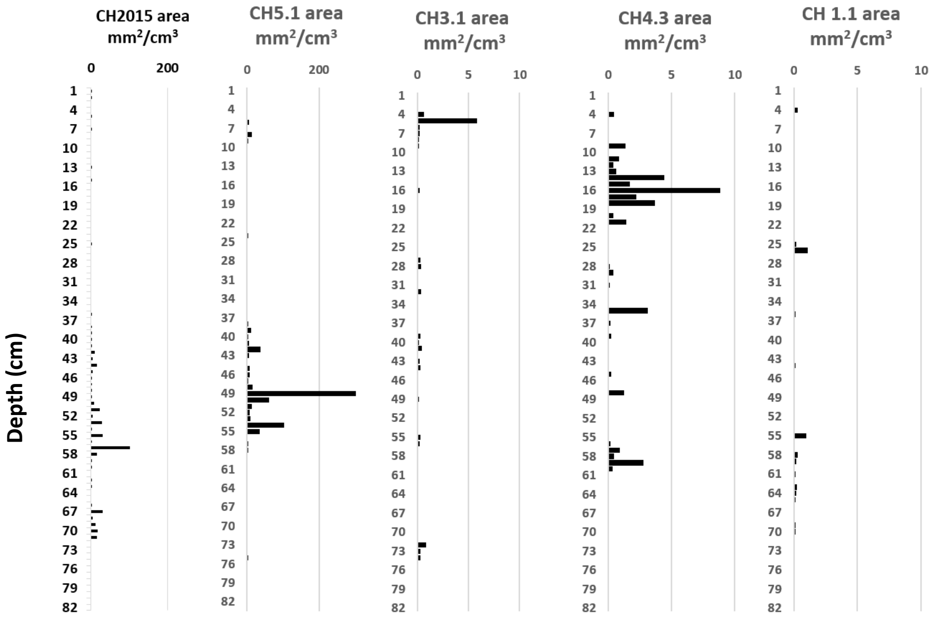
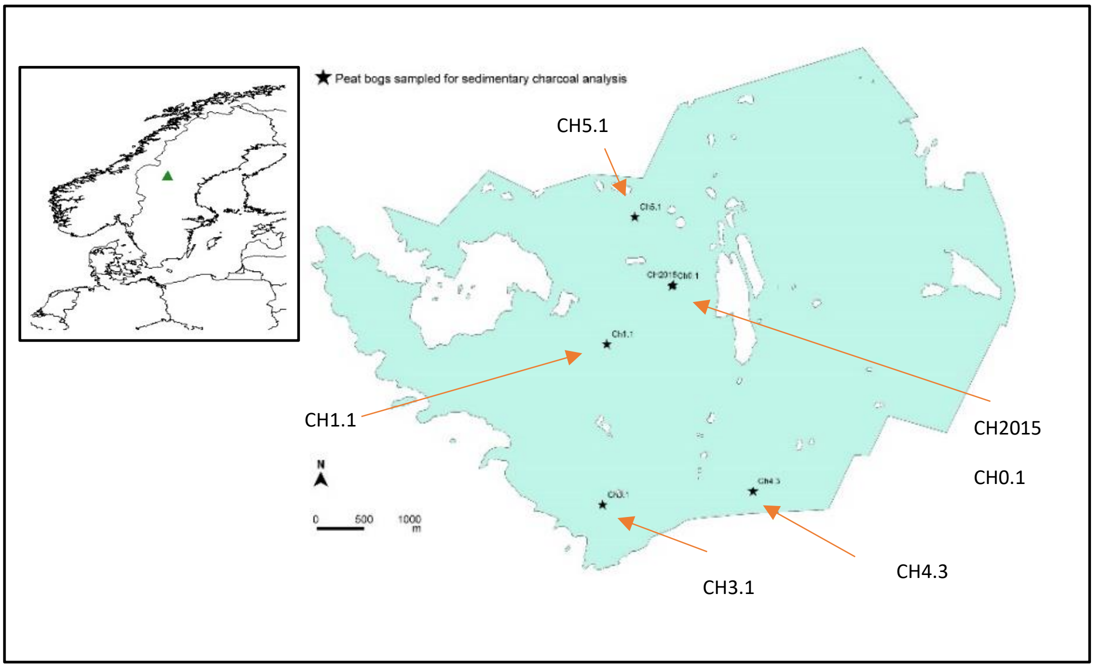
Annexe 1

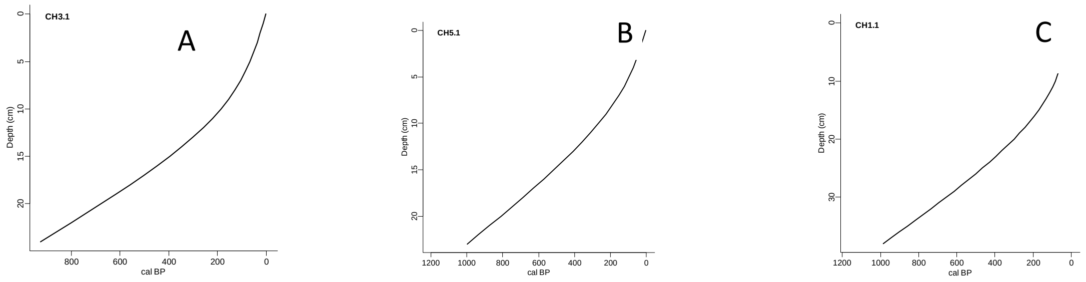


Five cores taken from Jamtgaveln Nature Reserve, Sweden in 2015 showing macrocharcoal concentration.

These macrocharcoal records show the variability in macrocharcoal abundance for multiple cores taken from the same site.



Jamtgaveln Nature Reserve, Sweden.



Age/depth diagrams for cores CH3.1 (A), CH5.1 (B), and CH1.1 (C), This is part of an ongoing project in development (Chiara Molinari, Lund University).

Variation between cores taken from the same site can be seen in the results for Jamtgaveln (figure 3.17). Here there is considerable variation between the cores in terms of temporal abundance. The distance between CH5.1 and CH3.1 is 3.163 km (Figure 3.18) so temporal difference abundance could be due to the size of the site and different assemblages around the site (figure 3-17). The age depth model has been completed for only three of the cores (figure 3.19).

RDA values for sites used in this study

RDA values (moving window)								
BB	CL	RH3	RM	SR	TT	C	G	S
6.762277	4.801008	7.568763	20.13049	23.65833	23.65833	27.65245	3.889853	] 10.41058
5.285386	6.580771	6.535703	20.96556	16.64142	16.64142	28.22042	3.305788	10.34151
5.029736	9.05438	10.34063	17.03433	15.46328	15.46328	28.5388	3.324804	11.4646
6.160791	4.792303	10.94346	12.95101	7.971565	7.971565	29.08793	3.088807	13.77193
4.375404	3.868774	14.07093	12.15342	6.652437	6.652437	12.91366	3.76452	14.01773
6.45165	8.416334	11.7918	7.349809	7.846072	7.846072	12.30124	4.830159	15.99415
11.84896	19.14421	12.7659	7.840545	8.361027	8.361027	12.45189	7.24009	12.01262
15.18597	16.93228	11.95568	7.24097	9.082035	9.082035	12.76851	7.963787	13.27847
8.744859	11.68842	20.07892	7.155128	8.427231	8.427231	14.55136	8.006044	12.8594
9.929841	9.907494	17.02955	6.985984	7.596372	7.596372	15.63667	7.370592	11.04754
8.953351	12.6607	17.685	7.121245	6.81941	6.81941	15.16126	8.785499	9.92678
7.271237	14.31364	13.05243	8.066283	7.904618	7.904618	14.48415	8.529064	9.847968
6.580824	11.86123	15.02402	6.424518	8.615389	8.615389	14.74211	7.184624	8.108506
10.02985	11.57193	14.4348	7.085287	8.71857	8.71857	14.70103	7.634067	0
11.06325	12.17281	12.99132	7.422146	9.080269	9.080269	14.11082	7.53448	0
12.9474	11.42927	11.48998	7.619581	7.453112	7.453112	14.04674	6.55004	8.716943
12.76224	9.940218	12.29348	10.25109	6.832638	6.832638	18.29866	5.279854	7.522448
18.59687	18.17769	12.65744	9.279322	9.09638	9.09638	18.53052	6.936739	10.17189
16.71057	18.29419	11.11086	9.976987	10.86957	10.86957	24.37833	6.410058	13.38321
8.892404	16.8543	13.41978	9.651695	9.15437	9.15437	23.40581	7.24735	13.86739
6.644627	14.38994	8.290823	8.554248	14.47843	14.47843	19.12114	7.262768	16.4349
6.156007	9.612859	7.869794	8.872365	15.85037	15.85037	18.52335	7.605187	17.68226
5.756634	10.36914	5.985877	9.431896	12.56864	12.56864	9.7818	7.887763	14.33157

7.233966	5.722111	5.993686	10.86712	13.14647	13.14647	9.412854	8.261976	12.24381
13.34005	6.528214	10.39244	11.12249	13.11576	13.11576	10.07248	8.204022	9.630336
13.02746	7.219398	9.450318	10.99462	12.69634	12.69634	10.95209	10.63636	7.774574
10.67647	5.786832	9.574082	12.39153	13.62352	13.62352	10.49736	9.891342	15.2894
13.82475	8.137245	10.75242	11.64509	15.69078	15.69078	11.27067	9.993135	20.87687
23.77844	10.03699	20.58811	10.99923	14.94258	14.94258	10.03895	10.61885	18.11923
21.39659	9.489148	19.11981	6.1141	15.46876	15.46876	9.729785	11.45021	18.08678
16.35551	9.63814	18.9946	6.612846	14.86326	14.86326	11.48823	12.33492	21.61966
13.52336	13.27161	19.86112	4.877263	16.20372	16.20372	9.024958	11.86729	24.84625
10.03268	15.33879	19.74741	5.868319	12.07298	12.07298	23.58256	12.24597	22.05102
7.656324	15.77133	17.88032	5.961023	12.4175	12.4175	19.40258	12.35038	26.68263
6.542389	15.45707	13.69563	10.13146	5.884671	5.884671	13.84547		16.8577
7.409327	17.94936	13.91999	10.74003	4.491617	4.491617			
7.2797	12.58923	11.63542	14.3621	4.703906	4.703906			
9.570628	8.513251	11.99782	18.196	4.710624	4.710624			
9.146856	8.977298	11.62696	13.2663					
14.8389	8.770933	13.51305	12.89968					
13.98466	8.178837	15.53546	12.59467					
7.143413	8.781156	15.25752	13.08699					
6.877395	9.04325	16.11196	12.987					
7.11587	9.267825	16.434	12.11354					
7.418317	8.71131	18.88383	6.420448					
	9.681068	22.28632	6.976821					
	8.330563	25.39489	8.744443					
	15.92607	20.84543	10.90093					
	13.22767	17.52282	10.31061					
	9.752069	21.53376	10.38581					
	9.575189	9.004935	8.787989					
	9.920621	12.91633	7.394187					
	12.65178	12.17598	6.852804					
	11.64848	14.45038	6.485991					
	23.0197	10.65549	6.776024					
	19.79718	15.94351	10.7487					
	15.51262	12.35225	9.560248					
	16.49241	11.28569	10.73774					
	13.94035	9.450018	5.719172					
	14.84869	10.52652	5.494977					
	11.77396		4.331442					
	11.87451		4.897836					
	12.56636		4.74204					
	11.79489		8.63708					
	7.775231		4.491473					
	11.14481		6.302565					
	10.05405		5.458891					
	8.923912		3.449815					
	10.30835		3.570397					
	9.415087		3.775567					
	7.694585		4.518315					
	8.241251		5.495691					
	10.75396		5.333594					
	8.972301		5.531067					
	9.714004		9.100087					
	13.1722		14.14462					
	12.99207		11.79818					
	10.37804		8.441164					
	10.24984		11.29341					
	8.398788		12.2512					
	9.3638		11.20356					
	12.93604		12.21462					
	15.58972		13.5137					
	15.53739		15.1782					
	12.53189		16.88538					
	11.4998		14.09814					

13.14308	12.66309
9.518194	10.25731
11.14728	9.12403
6.843527	9.046258
6.698402	8.394538
9.036358	9.434549
7.796469	8.115061
6.403981	8.501838
6.706779	8.525682
7.669608	6.231125
7.268384	7.704508
9.356276	7.697064
10.08043	10.58355
11.46761	9.652227
13.64833	10.4258
10.37029	10.90199
7.211278	8.189607
8.577769	8.568568
	9.362006
	6.008223
	4.986536
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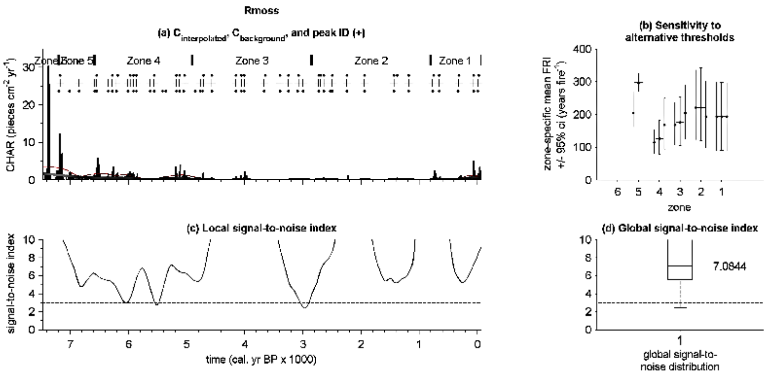
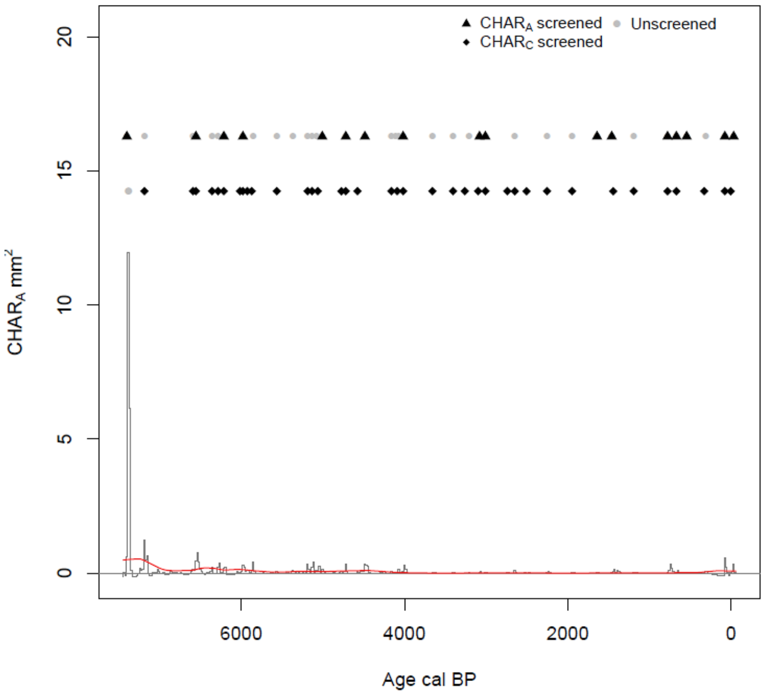
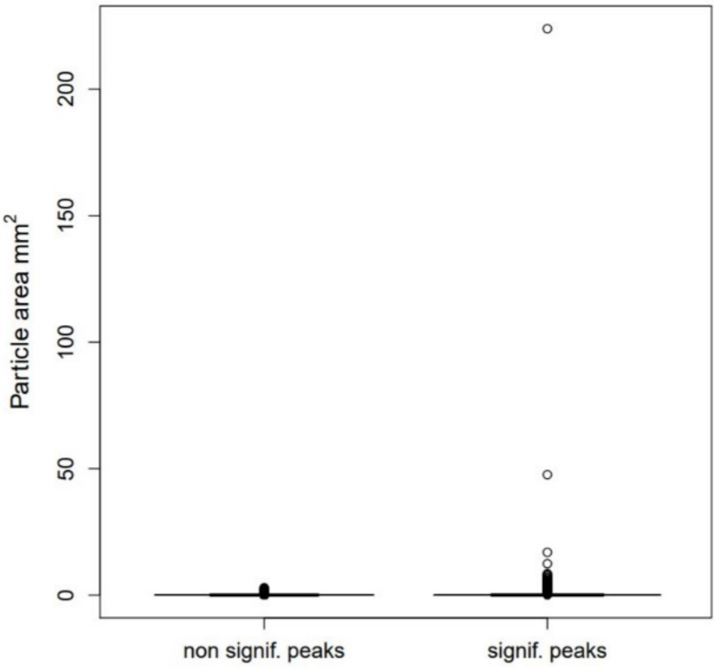


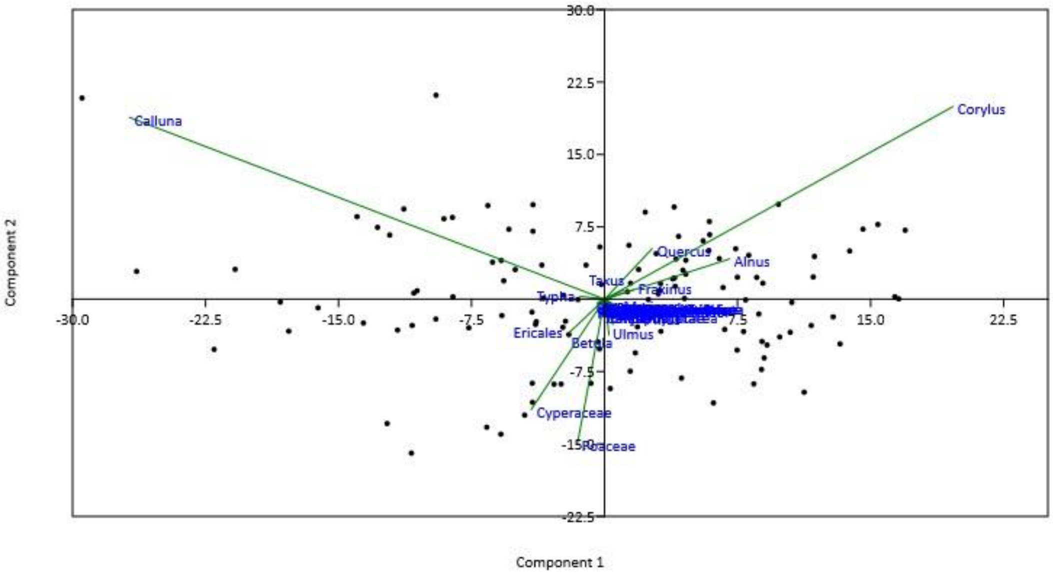
The signal to noise index (SNI) almost entirely exceeded the critical threshold of 3.0 over the record. This implies that the macrocharcoal count data is suitable for peak-detection analysis (Kelly, 2011).



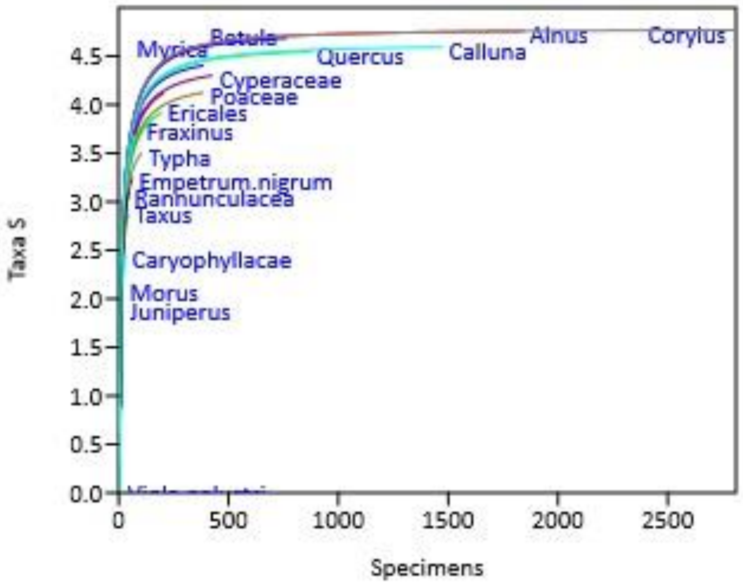
Char$_A$ peaks shown by black triangles were bootstrapped charcoal-area measurements were simulated by random sampling (with replacement) from distributions of observed areas of individual charcoal particles (Finsinger, 2014).



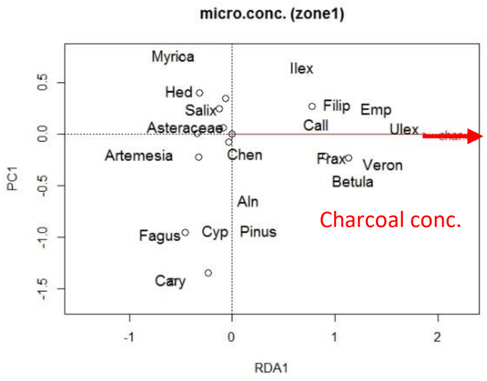
Comparison between charcoal fragment area distributions for charcoal peaks that did not survive the screening peaks test (non significant peaks) and these that did (significant peaks). Non-overlapping means suggest that the medians are significantly different (Finsinger, 2014).

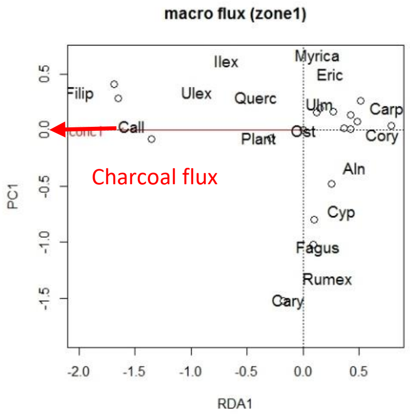


PCA1 plotted with PCA2 for Robinsons Moss (pollen percentages)

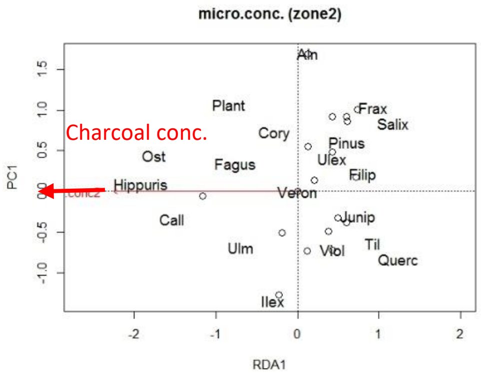


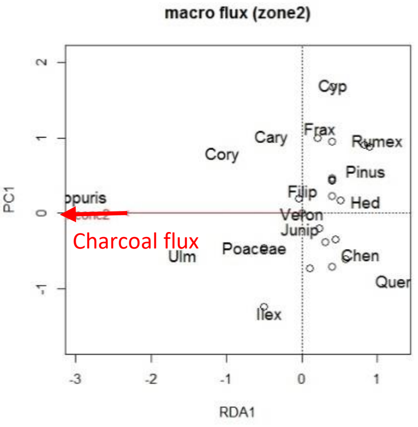
Diversity index for Robinsons Moss



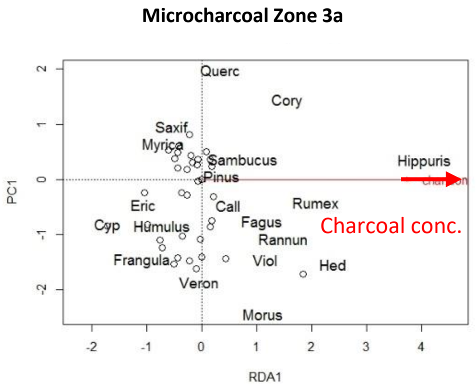


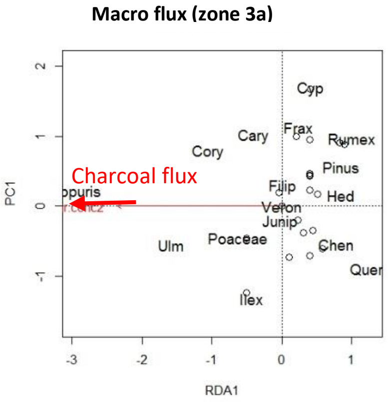
Zone 1



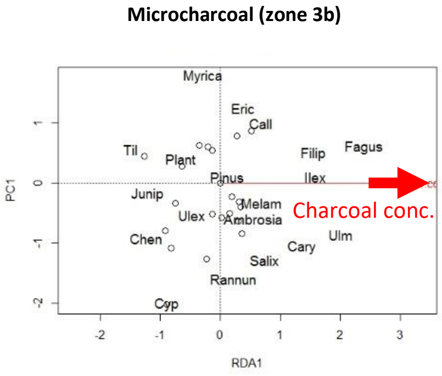


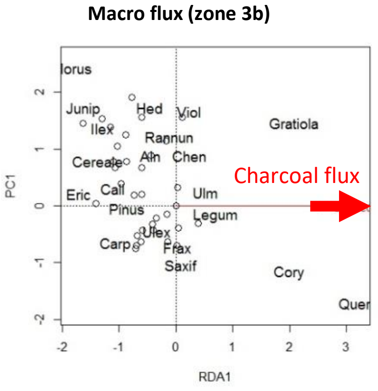
Zone 2



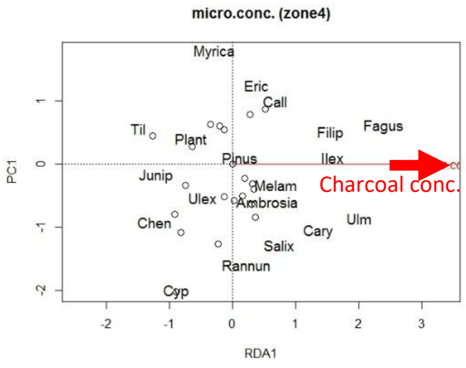


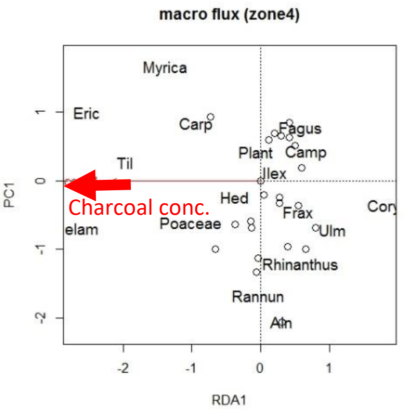
Zone 3a



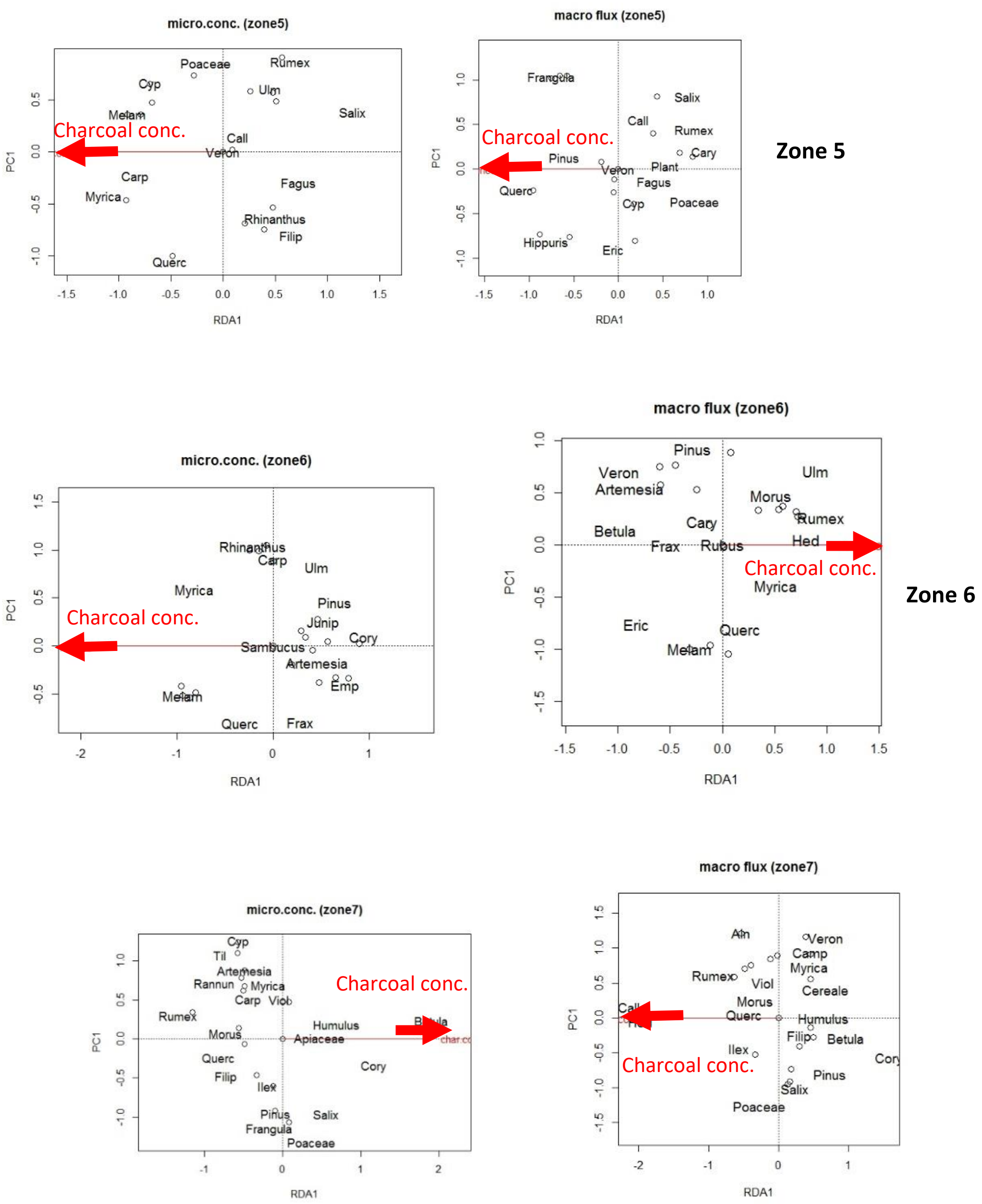


Zone 3b

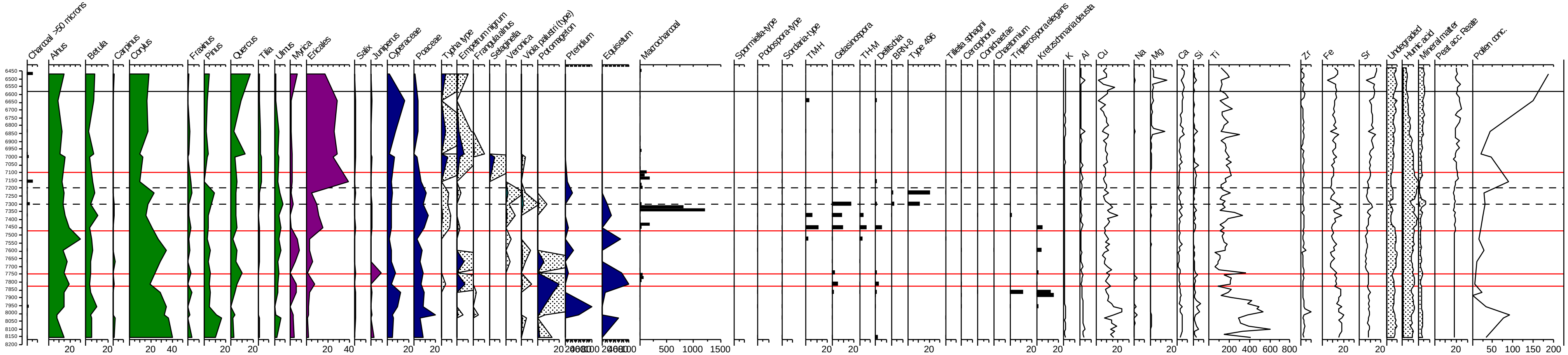




Zone 4



Pollen taxa distribution on PC1 with charcoal (macro and micro) as the explanatory variable (RDA1).



Tilia graph (Blauuw, 2010) for a section of the Robinsons Moss data (8200 – 6500 years BP) showing macrocharcoal influx (mm^2/cm^2/yr^{-1}), pollen percentages; XRF analysis for a selection of elements (ppm); NIRS (ppm)

Annex 2

Other published papers where Karen Halsall is a co-author are listed below.

BRADLEY, L. R., GIESECKE, T., HALSALL, K. & BRADSHAW, R. H. W. 2013. Exploring the requirement for anthropogenic disturbance to assist the stand-scale expansion of Fagus sylvatica L. outside southern Scandinavia. *Holocene,* 23**,** 579-586.

CARTER, V. A., MORAVCOVA, A., CHIVERRELL, R. C., CLEAR, J. L., FINSINGER, W., DRESLEROVA, D., HALSALL, K. & KUNES, P. 2018. Holocene-scale fire dynamics of central European temperate spruce-beech forests. *Quaternary Science Reviews,* 191**,** 15-30.

MARRS, R. H., MARSLAND, E. L., LINGARD, R., MILLIGAN, G., ALLEN, K. A., ALDAY, J. G., SANTANA, V., LEE, H., HALSALL, K., CHIVERRELL, R. C., APPLEBY, P. G., PILIPOSYAN, G. T., ROSE, R. J. & O'REILLY, J. 2018. Experimental evidence for sustained carbon sequestration in fire-managed, peat moorlands. *Nature Geoscience*.

OVERBALLE-PETERSEN, M. V., NIELSEN, A. B., HANNON, G. E., HALSALL, K. & BRADSHAW, R. H. W. 2013. Long-term forest dynamics at Gribskov, eastern Denmark with early-Holocene evidence for thermophilous broadleaved tree species. *Holocene,* 23**,** 243-254.

Paper to be presented at INQUA, Dublin, 2019

Abrupt late Holocene ecosystem change in central European mountain forests; Kuosmanen, N., K. Halsall, Svitavska Svobodova, H., Beranova, J., Hannon, G., Fleischer, P., Chiverrell, R.2, Kuneš, P. & Clear, J.L