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Quantifying Fire Regimes and their Impact on the Irish Landscape

Ph.D

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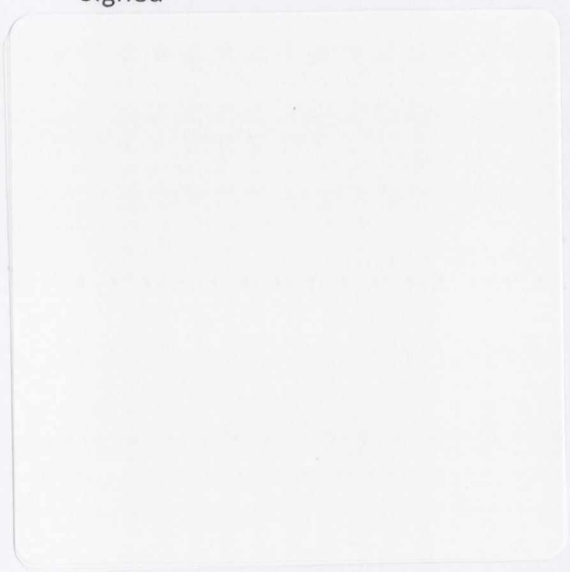
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Summary

This thesis examines the role of fire in the Irish landscape in the past, its drivers, impacts and interactions with the surrounding landscape, vegetation, climate and humans. Lacustrine sediment is utilised from seven study sites from a range of locations throughout Ireland, from upland, lowland and midland sites, to provide a multi-proxy record of charcoal and pollen. Four main research questions are addressed;

1. What was the nature and scale of fire in the Irish landscape in the past?
2. Are there common trends in fire that can be identified on a national and international scale?
3. How did this fire impact the surrounding landscape and vegetation?
4. Does fire have an impact on biodiversity and on what level?

A number of laboratory and statistical methods have been adopted to explore these research questions. Past fire regimes were reconstructed using digital charcoal counting methods and CharAnalysis software. An ensemble member strategy, signal to noise index and charcoal peak screening method were used to help validate these reconstructions. Vegetation reconstructions are carried out using standard palynological techniques, with a spearman's correlation and t-test used to try and identify any relationships that may exist between specific taxa and charcoal concentrations. An NMDS ordination is also carried out to identify any similarities between pollen samples. The biodiversity at each site is assessed using a number of diversity indices i.e. Shannon and Simpson's Indexes and Pielou's and Simpson's Evenness. The diversity is compared between study sites using a rarefied species richness technique and an ANOVA analysis. The relationship between biodiversity and fire is examined, by carrying out a t-test before and after each fire event in a 200 year time window. Trends in fire are examined between the study sites in Ireland visually and using a k-s test on charcoal concentrations. Comparisons are made between the fire return intervals

and peak magnitudes using a Weibull likelihood ratio test. Finally a charcoal synthesis is carried out using the new Paleofire package in R (Blarquez et al., 2014) to create a composite record of fire for Ireland. This composite record can then be compared to trends in fire from a range of locations to determine if common trends in fire exist on a range of geographical scales.

The identified fire events, their magnitude and frequency varies significantly between the 7 study sites examined. Results suggest that fire events were occurring within similar time periods or under similar vegetation and climate conditions, and are seen to be increasing towards the present day. The highest periods of change and instability identified throughout the Holocene are generally seen to be associated with the identified fire events at each site.

From the palynological investigations specific species can be designated as fire adapted (*Quercus, Pinus* and *Poaceae*), fire dependent (*Corylus, Alnus, Pinus* and *Salix*), fire resistant (*Betula, Quercus, Pinus,* Poaceae and *Calluna*) and fire sensitive (*Ulmus*). Biodiversity was identified to significantly change following a fire event, and fires with a higher magnitude have an increasingly negative impact on biodiversity. The composite record of fire from Ireland was found to follow similar trends in fire from the UK, Europe, North America and the World, and increases or decrease in fire activity on a large scale can be correlated with changes in climate such as temperature, precipitation and CO_2. On a smaller scale individual site conditions such as topography, soil type, vegetation and meteorological conditions influence fire occurrence. This thesis represents the first study of its kind in Ireland and examines the record of fire and its interactions on a multi-site and palaeoecological time scale.

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Chapter 1

Introduction

1.1 General Introduction

Fire is the dominant disturbance factor in most terrestrial ecosystems (Bowman et al., 2009) and has been an integral part of the Earth's system for the past 350 million years (Scott and Glasspool, 2006). Fire activity has varied globally and continuously in response to long-term changes in climate, vegetation and anthropogenic activity (Power et al., 2008). The future susceptibility to fire is expected to be high (Flannigan, 2009, Girardin and Mudelsee, 2008), with changes in climate such as increased temperatures, drier summers and a 20% reduction in precipitation (Gleeson et al., 2013), the frequency and severity of fires within Ireland is expected to increase. Within Ireland significant changes in vegetation, land use, agriculture and policy, have also promoted an increase in fires in the Irish landscape in recent years. It is therefore important to understand the interactions and drivers of fire to help manage and mitigate against its destructive impacts for the future (Marlon et al., 2009).

To fully understand climate fire linkages an integrated palaeoecological and ecological approach is needed (Iglesias et al., 2014, Peng et al., 2011). There are a number of recent studies that combine both disciplines and demonstrate the value of empirical palaeoecological records to describe past fire regimes (Brubaker et al., 2009, Heiri et al., 2006, Bradshaw, 2008, Colombaroli et al., 2010, Henne et al., 2013, Brücher et al., 2014). A wide range of analytical techniques have been developed which use sedimentary charcoal as a fire proxy for fire history reconstructions (Whitlock and Larsen, 2002). Many studies

adopt a multi-proxy approach utilising lake sediment records which contain proxies such as pollen grains, charcoal fragments, plant macrofossils, chrominids, diatoms, phytoliths and soil geochemistry, which can be used to reconstruct the character of the past landscape, past climatic conditions, catchment processes and identify extreme events occurring within the surrounding landscape (Smol, 2009, Birks and Birks, 2006, Michelutti and Smol, 2013). Lakes represent one of the best archives for palaeoenvironmental information, and palaeolimnology i.e. the study of past conditions and processes in lakes, is now a well-established and constantly evolving discipline (Last et al., 2001).

Macrocharcoal (particles >125 µm in diameter) has been used as a proxy to reconstruct local fire history, as this size of charcoal is expected to have a high settling velocity which is associated with local source areas (<20 km from the lake) (Higuera et al., 2011). Statistical analysis of macrocharcoal via the CharAnalysis programme (Higuera, 2009) allows the reconstruction of fire events, fire frequency, fire magnitude and fire return intervals. As research progresses in the area of fire history reconstruction an ever increasing range of software is emerging which builds on previous analyses. An ensemble member strategy has been recently developed which aims to remove the objectivity from the analytical choices of the CharAnalysis programme (Blarquez et al., 2013). An improved signal to noise index calculation has also been established which determines if a sedimentary charcoal record is appropriate for peak detection (Kelly et al., 2011). And most recently a charcoal peak screening method has been devised by Finsinger et al. (2014) to screen charcoal peaks to determine if they were identified by chance variation or can be classified as real fire events. Archaeological studies can also contribute significantly to the analysis of past fire regimes; larger charcoal pieces (>250µm) from such sites can be used to determine their taxonomic origin, inferring which

vegetation was being burnt locally. They also provide an important record of human activity in the area which may help deduce the origin of the fire.

Humans have been using fire as far back as 1,000,000 years ago (Berna et al., 2012) and their impact on natural fire regimes has changed as economies have shifted from hunter-gatherers to pastoralisation, to farming and to industrialisation (Pyne, 2001). However studies examining human-fire relationships at continental scales over millennia (Marlon et al., 2008) have attributed climate as the dominant driver of fire activity (Daniau et al., 2010, Mooney, 2011, Power et al., 2013). Due to the complex nature of human, climate and fire interactions, disentangling the cause of fire from the palaeoecological record is an ongoing challenge.

Fires are complex ecological processes, which are driven by factors acting at a variety of scales, higher-level spatial factors constrain the effects of more local ones to various degrees (Turner, 2001). Studies of past biomass burning are grounded in this conceptual understanding of top-down and bottom-up influences on fire occurrence (Iglesias et al., 2014). Therefore interpreting past fire activity focuses on unravelling large scale controls of fire such as climate and vegetation, from local controls related to site characteristics, fuel conditions, and human activity (Whitlock et al., 2010).

There is a constantly growing geographical coverage of high resolution charcoal data which will add to the knowledge of the drivers of fire and understanding their interactions in a variety of spatial scales. The Global Palaeofire Working group (www.gpwg.org) supports a public-access database of fire records and has created a computer code for the synthesis and analysis of charcoal data (Blarquez et al., 2014). This allows the collaboration of composite records on a range of spatial

scales, helping to deduce trends in fire in the past and make predictions for the future (Marlon et al., 2012).

Currently a number of trends have been identified to exist globally; an increase in fire activity is observed in the mid to late Holocene due to changes in vegetation (Daniau et al., 2012).The type of vegetation change observed is region and biome specific but can include an increase in flammable species, a decrease in woodland, increase in peatland and increased fuel load (Whitlock et al., 2003). Fire activity is also proposed to have increased during the late glacial to early Holocene transition in association with rising temperatures (Marlon et al., 2009). Increased temperature enhances fire supporting weather through increased storm intensity and lightening ignitions (Daniau et al., 2012). Long-term trends in global biomass burning attributed to climate change, correlate well with temperature and charcoal trends (Daniau et al., 2012). It has also been suggested that changes in CO2 can reflect changes in biomass burning. Carcaillet et al. (2002) provided one of the first syntheses of continental scale palaeofire data examining the interaction of fire and atmospheric CO_2, suggesting that there has been a parallel increase in CO_2 and biomass burning since the Last Glacial Maximum. During the past two centuries, anthropogenic activities dominate the global biomass burning signal (Marlon et al., 2012), and factors such as population growth, fire suppression, land use change, agriculture, overgrazing, urbanisation and invasive plants, have caused changes in fire regimes (Bowman et al., 2011).

1.2. Justification for Research

The island of Ireland provides the perfect backdrop for palaeoenvironmental research, its location on the edge of Europe and at the edge of the Atlantic provides the perfect setting to study long

term changes in climate. Climate drives all major ecological processes on earth, controlling how plants colonise and spread, affecting extreme events such as wildfires, and dictating local weather patterns. These interactions can be traced in the palaeoecological record, and this record for Ireland extends back to the Late Glacial and into the Holocene, some 15,000 years ago, before the occupation of humans. This is an important record as prior to human occupation, all changes were controlled by natural influences in the atmosphere. Wildfire has been occurring in Ireland since the last deglaciation, and has been documented to increase in the last 20 years. Its effect and severity is also projected to increase with future climate change. Increased temperature and reduced rainfall will intensify the effects of wildfire on the landscape.

Currently there has been little previous study of wildfire in Ireland, and no study has looked at the effects of fire at multiple sites in a palaeoecologcial context. This study utilises lacustrine sediment cores from seven study sites in a range of ecosystems throughout Ireland. Upland sites are located in the Galty (Borheen and Diheen Lough) and Wicklow (Kelly's Lough) Mountains, and lowland sites in Killarney National Park (Cuckoo and Sheheree Lough) and the Irish Midlands (Ballinderry and Cornaher Lough). These sites were selected due to the nature of the sediment record, the appropriateness of the study sites, the availability of previous data, and location.

1.3 Project Aims

The aim of this study is to provide an accurate reconstruction of the past fire regime at each of the study sites. To exploit current and new methods in charcoal analysis and fire history reconstruction, and assess the impact of fire on the surrounding landscape. By carrying out a vegetation reconstruction at each study site and examining the impact

of fire, any taxa which may be fire-sensitive, fire-dependent, fire-resistant or fire-adapted may be identified. The biodiversity at each study site is also examined to assess and quantify the impact of fire. Finally a composite fire record for Ireland will also be created, which can be compared to trends in fire from the UK, Europe, North America and the World.

1.4 Project Objectives

To achieve the aims outlined previously a number of laboratory and statistical methods are adopted. Digital charcoal counting is applied on all charcoal samples to quantify the amount of charcoal in each cm of the cores. This record is then used to model the past fire regimes at each site via CharAnalysis software (Higuera, 2009). This method is backed up by an ensemble member strategy (Blarquez et al., 2013) to aid parameter selection, a signal to noise index (Kelly et al., 2011) to assess if the record is appropriate for peak detection and a charcoal peak screening (Finsinger et al., 2014) process to ensure that the fire events identified are 'real fire events'. These analyses provide a record of specific fire events, their magnitude, frequency and fire return interval.

Vegetation reconstructions are carried out using standard palynological techniques, to provide a record of the taxa present throughout the Holocene at each site. A Spearman's correlation is carried out to try and identify any specific relationship that may exist between specific taxa and charcoal concentrations. A t-test is also carried out to assess how vegetation changes before and after a fire event, and may identify vulnerable or fire resistant taxa. Finally an NMDS ordination is carried out to identify how similar pollen samples at each site are, to determine times in the past where environmental and vegetation conditions were similar.

The biodiversity at each site is assessed using a number of diversity indices such as the Shannon and Simpson's Indices and Pielou's and Simpson's Evenness. The diversity is plotted using a species accumulation curve and rank/abundance plots to visually display changes in biodiversity over time. Diversity is compared between study sites using a rarefied species richness technique and an ANOVA analysis. Finally the relationship between biodiversity and fire is examined by carrying out a t-test before and after each fire event in a 200 year time window to assess the impact of fire on biodiversity. The magnitude of fire necessary to affect biodiversity was also tested with selected fire events to identify a threshold for biodiversity impact.

Finally trends in fire are examined between the study sites in Ireland visually and using a k-s test on charcoal concentrations. Comparisons are also made between the fire return intervals and peak magnitudes using a Weibull likelihood ratio test. Finally a charcoal synthesis is carried out using the new Paleofire package in R (Blarquez et al., 2014) to create a composite record of fire for Ireland. This composite record can then be compared to trends in fire determined from other lacustrine sites, from a range of locations. This will determine if common trends in fire exist on a range of geographical scales, and give an insight into the different drivers and controls of fire at these scales.

This study represents the first of its kind in Ireland and will provide a baseline level of data which can be built on in future scenarios when fire frequency and severity is expected to increase. It is important to utilise the knowledge gained from such studies to inform management and guidelines which can help to limit the potentially devastating effect of fire in the future.

1.5 Research Questions and Thesis Outline

This thesis is divided into 4 analytical chapters, which address the four main questions arising in this project;

1. What was the nature and scale of fire in the Irish landscape in the past?
2. Are there common trends in fire that can be identified on a national and international scale?
3. How did this fire impact the surrounding landscape and vegetation?
4. Does fire have an impact on biodiversity and on what level?

Chapter 2 outlines the laboratory and analytical methods used to prepare the samples collected in conjunction with this thesis, while Chapter 3 presents a comprehensive outline of the study sites divided into their respective regions of Ireland; the Irish Midlands, the Galty Mountains, Killarney National Park and the Wicklow Mountains. Chapter 4 addresses the first research question and identifies the past fire regime at each of the sites throughout the Holocene. Chapter 5 compares the pattern of fire between the different study sites and regions within Ireland, and uses the composite Irish record to compare the record of fire to trends from the UK, Europe, North America and the World. Chapter 6 examines the relationship between fire and vegetation at each site, and attempts to identify any fire related characteristics associated with specific taxa. Chapter 7 addresses the final research question and examines the impact fire has on biodiversity, and investigates how biodiversity has changed over time at each site. Finally Chapter 8 provides a discussion and conclusion of the results obtained from each chapter, and any possible future recommendations.

1.6 Abbreviations and Acronyms

AD	Anno Domini
ANOVA	Analysis of Variance
BP	Refers to cal.BP calibrated years before present
C_A	Charcoal Area
$C_\#$	Charcoal Count
$Char_{raw}$	Raw Charcoal Accumulation Rate
$Char_{peak}$	Peak Series (detrended charcoal series)
$Char_{back}$	Background Charcoal
$Char_{fire}$	One additive component of Charpeak
$Char_{noise}$	Second additive component of Charpeak
$Char_{area}$	Charcoal Area
$Char_{count}$	Charcoal Count
C.I.	Confidence Interval
CH_4	Methane
CO_2	Carbon Dioxide
FF	Fire Frequency
FRI	Fire Return Interval
GCD	Global Charcoal Database
GoF	Goodness of Fit
Ka	Thousand years
LRT	Likelihood Ratio Test
LOI	Loss on Ignition
MRPP	Multi Response Permutation Procedure
NGO's	Non-Governmental Organisations
NMDS	Non Multi-Dimensional Scaling
N	Noise
PerMANOVA	Permutational Multivariate Analysis of Variance
ROC	Rate of Change
SNI	Signal to Noise Index
S	Signal

Taxa are referred to in Latin and Italicised where appropriate. Family names not italicised.

1.7 Archaeological Periods

Table 1.1 Archaeological Time Periods

Archaeological Time Period	**Age (BP)**
Palaeolithic	Pre 10,000
Mesolithic	10,000-6,000
Neolithic	6,000-4,400
Bronze Age	4,400-2,500
Iron Age	2,500-1,600
Medieval Period	1,600-300
Modern	300-0

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Chapter 2

Materials and Methods

2.1 Introduction

This chapter presents all the laboratory and analytical methods used in the preparation of the samples obtained in conjunction with this thesis. Table 2.1 overleaf states any previous work which has been completed, organised by study site, and any analysis completed as part of this thesis marked with the initials 'DH'. For information regarding methods used in previous analyses please consult the appropriate references mentioned overleaf. Details and software associated with specific data analysis are outlined where appropriate in subsequent chapters.

2.2 Data Acquisition from previous studies

As stated in Table 2.1 data generated in association with previous studies and sites was used. These sites were selected based on the availability of the data, the site type i.e. lake site, and location. Cuckoo Lough in Killarney was cored to supplement the data from other sites in the area, to provide a link to data on known fire history, and provide the opportunity to tailor the resolution of the pollen analysis here to match identified fire events. This is the only site which is entirely unique to this thesis. All other sites had existing pollen, radiocarbon, and loss on ignition data, which was available in the form of an Excel or Tilia spreadsheet and used for further analysis. Kelly's Lough and Ballinderry Lough had existing charcoal data which was utilised for this study, but all other charcoal data was generated as part of this research.

2.3 Fieldwork and Core Collection

Fieldwork was carried out in June 2012 at Cuckoo Lough, a small lake located in the North East of Killarney National Park (site description, see Chapter 3). A surface core of 1m in depth was obtained, as well as two overlapping cores extending to a depth of 6.52m. A Livingstone piston corer (Livingstone, 1955) was used to extract the sediment cores, which were wrapped in cellophane and aluminium foil before being transferred and stored in the cold room at Trinity College Dublin. The surface core was extruded onsite at 1cm intervals and stored in sample bags for further analysis.

2.4 Core Preparation and Sub-sampling

Before any further laboratory analysis all cores were cleaned to prevent any contamination that may have occurred during transportation, this involves removing a small amount of the surface material from the core in a systematic manner. Each core was then described using the *'Classification of lacustrine sediments based on sedimentary components' (Schnurrenberger, 2003)*, which provides an objective method of core description, with any distinguishing features being recorded. Finally all cores were sliced into sub-samples of 1cm thickness, which were stored in separate, carefully labelled sample bags to await further analysis.

Table 2.1 Site description including location, authorship of work completed and published source.

Study Site	*Cuckoo Lough*	*Diheen Lough*	*Sheheree Lough*	*Borheen Lough*	*Cornaher Lough*	*Kelly's Lough*	*Ballinderry Lough*
Location	Co. Kerry	Galty Mountains	Co. Kerry	Galty Mountains	Co. Westmeath	Co. Wicklow	Co. Westmeath
Fieldwork	**DH**	ML	TC	ML	AH	ML	EOC
Pollen Analysis	**DH**	EC	TC	EC	AH	EC	EOC
Loss on Ignition	**DH**	EC	TC	EC	AH	EC	EOC
Charcoal Analysis	**DH**	**DH**	**DH**	**DH**	**DH**	AM	CB
Radiocarbon Dating	**DH**	EC	TC	EC	AH	EC	EOC
Data Analysis	**DH**	**DH**	**DH**	**DH**	**DH**	**DH**	**DH**
Source	PhD Thesis (**DH**)	Unpublished Paper (ML and EC) PhD Thesis (**DH**)	Book (TC) PhD Thesis (**DH**)	Unpublished Paper (ML and EC) PhD Thesis (**DH**)	PhD Thesis (AH and **DH**)	MA Thesis (AM) Published Paper (ML and EC) PhD Thesis (**DH**)	PhD Thesis (EOC and **DH**) MA Thesis (CB)

Key of Authorship: Alyson Heery (AH)(Heery, 1998), Aoife Murphy (AM)(Murphy, 2008), Cathy Brooks (CB)(Brooks, 2009), **Donna Hawthorne (DH)**, Edwina Cole (EC)(Cole and Mitchell, 2003) Ellen O'Carroll (EOC)(O'Carroll, 2012), Tom Cooney (TC)(Mitchell, 2004), Maniel Leira (ML)(Leira, 2010)

2.5 Charcoal Analysis

Charcoal analysis was carried out on all study sites using the same method, at 1cm intervals and was confined to particles greater than 125µm. This is due to the fact that calibration studies of charcoal have shown that during and after a fire event, charcoal particles >125µm are not transported far from the location of the fire, and are therefore a good indicator of local fire events (Whitlock, 2001). The charcoal analysis at Ballinderry Lough and Kelly's Lough was carried out as part of a previous project but uses the same laboratory methods outlined here. The method used here for the preparation of the samples is adapted from those described by Mooney and Black (2003) and Mooney and Radford (2001). Each 1cm subsample was treated with 40ml of a 15% solution of Calgon (Sodium Hexametaphosphate). The samples were then allowed to disaggregate on a flat-bed mechanical shaker for 24 hours, before being washed with a 125µm sieve. The material remaining on the sieve was treated with 40ml of undiluted domestic bleach and allowed to stand for a further 24 hours. After which the samples were washed for a second time with a 125µm sieve and transferred to pre-labelled petri dishes ready for digital image analysis.

2.6 Digital Image Analysis

Using a digital camera (Panasonic Lumix DMC-SZ1, no flash, AF Macro setting) a fine resolution image was captured of each petri dish from the previously described charcoal analysis. It is advised that a camera with a minimum 10 megapixels is used (Brooks, 2009). A camera stand was also used to ensure continuity between images. Once the images were captured and loaded onto the computer they were analysed via Image J software (Abràmoff, 2004). This software was preferred as it

allows a simple and easy method of charcoal counting, providing area as well as count for each image. The analytical method follows that similar to Schlachter (2012). Once the image is open within the software it is necessary to set a scale and unit of measurement. The area to be analysed is then selected using the circle tool, and the threshold colour adjusted so that all charcoal fragments are selected. The image is then analysed and a summary table produced containing the charcoal count and area for that image. There has been some criticism of digital charcoal counting (Whitlock and Larsen, 2002), claiming that not all fragments counted are adequately identified as charcoal pieces. However this was prior to the use of Image J software, which has become widely used as a valid method of charcoal counting (Stevenson and Haberle, 2005). This software allows the manual selection of charcoal particles via a colour threshold, not utilised in previous software. This ensures that only charcoal fragments are selected, and this can be checked under the microscope. Figure 2.2 (a) shows an example of a petri dish of charcoal used for the image analysis and the same dish post analysis Figure 2.2 (b). To address the difference between microscope and digital counting, 10 charcoal samples from Cuckoo Lough were also manually counted to compare methods. The results presented in Figure 2.1 overleaf show that there is little discrepancy between the two methods and concurs with a similar validation exercise completed by Stevenson and Haberle (2005). A correlation analysis was carried out on the 10 samples from Cuckoo Lough, to compare the microscope counted charcoal and the Image J counted charcoal. R software was used and a Pearson's product-moment correlation carried out. This produced a correlation of 0.9398 and a p-value of 0.0000531, this is a strong positive correlation which is highly significant. Prior to this analysis both sets of data were tested for normality using a quantile-quantile plot, and both follow a normal distribution. A two-sample Kolmogorov-smirnov test was also carried out to test if the microscope count and digital count data are

significantly different. This test proved that the two sets of data are not significantly different ($p>0.05$) with a p-value of 0.9883. This analysis would suggest that the Image J analysis is just as valid as the microscope analysis. This method of digital counting was used on all sites except Kelly's Lough where a similar technique was employed using Scion Image software.

2.7 Pollen Analysis

Pollen Analysis was carried out at Cuckoo Lough, Killarney and at all other sites in previous studies as outlined in Table 2.1. Pollen analysis on all sites follows the same standard procedures outlined below. Samples at Cuckoo Lough were analysed at 4cm intervals throughout the core, except for surrounding identified charcoal peaks where the resolution increased to 1cm intervals. The laboratory methods used have been adapted from Shackley (1981) which is outlined in Paleoethnobotany: A handbook of Procedures (Pearsall, 1989). One centimetre cubed of peat was used at each appropriate depth, with two *Lycopodium* tablets to enable pollen concentration calculations. The methods follow the standard procedures of initial preparation, alkali digestion, sieving, acetolysis and alcohol wash. Once mounted on microscope slides the pollen was counted and identified using the reference collection at Trinity College Dublin. Pollen and spore nomenclature follows Moore et al. (1991). During the laboratory preparations there was a recurring issue of 'clumping' on the pollen slides, rendering them uncountable. This situation was rectified by modifying various stages of the method i.e. mixing the samples on a whirlmixer, leaving the samples slightly longer in the waterbath, and repeating the alkali digestion stage. The pollen data was analysed in Tilia Graph, C2 and Microsoft Excel software, and a pollen diagram generated for Cuckoo Lough. Using similar software the pollen data

from the previous studies was used to reproduce diagrams for each site. A microscopic analysis of macrofossils was also carried out at each pollen depth (Mauquoy, 2011) and loss on ignition analysis was carried out on each cm of the core, to reveal any variation between organic and inorganic material found in the sediment. This data is based on differential thermal analysis i.e. the sample is weighed before and after ignition and the weight loss percentage determined by difference (Dean, 1974).

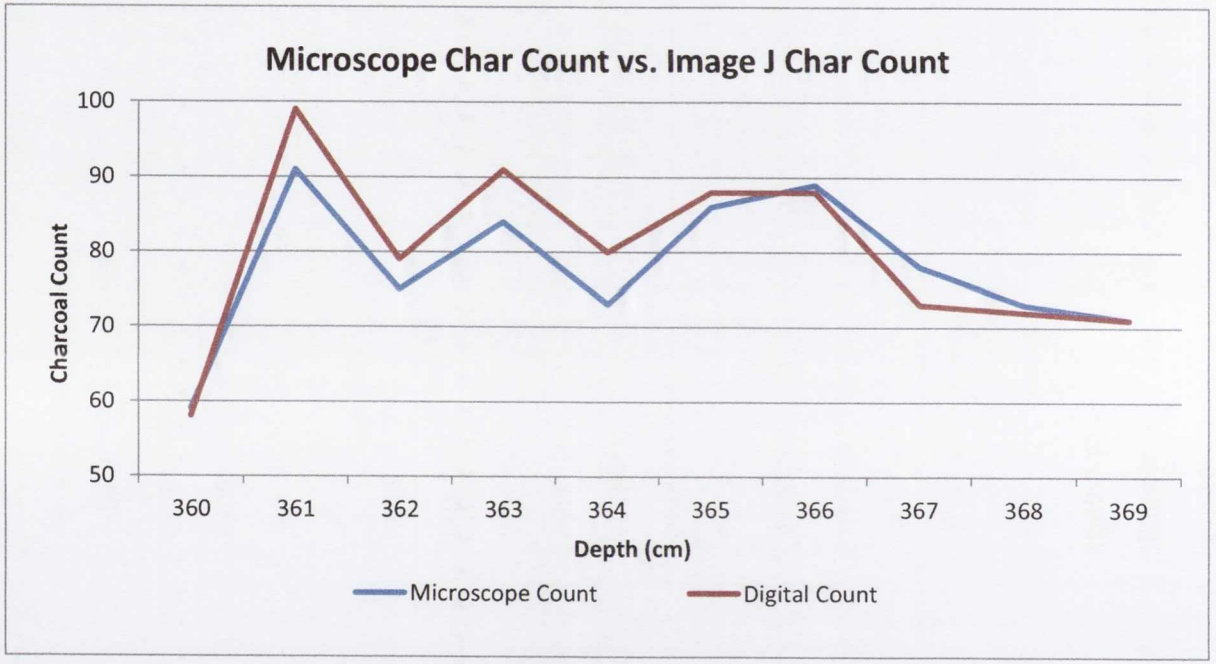
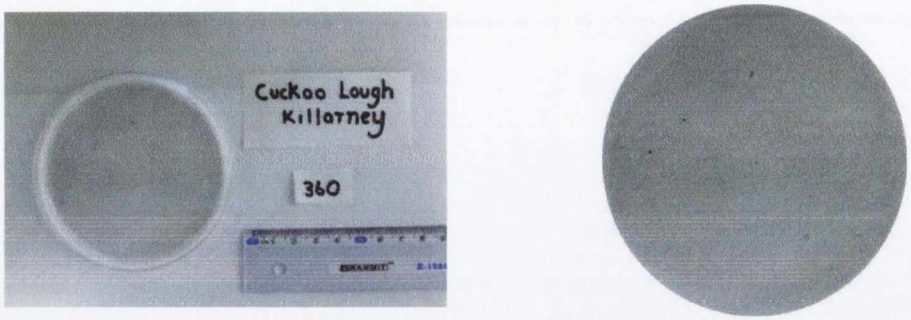


Figure 2.1 Graph illustrating the difference between microscope counted charcoal and charcoal counted using image analysis software



(a) (b)

Figure 2.2 Example of a petri dish of charcoal used for the image analysis (a) and the same dish post analysis (b)

2.8 Radiocarbon Dating

Dating provides an important context for each study site and it was carried out as part of the analysis on each sediment core. Table 2.2 overleaf shows details of all the radiocarbon dates obtained from each study site. Eight radiocarbon dates were obtained in conjunction with this thesis from Cuckoo Lough, Killarney, Co. Kerry. The dating was carried out by Queen's University Belfast's Chrono centre from bulk sediment extracted from the Cuckoo Lough core. All radiocarbon dates were analysed using BChron (Parnell et al., 2008), a statistical package in R, which uses Bayesian analysis to generate accurate age-depth models for each site. The resulting chronology for each of the sites can be seen in the appendix Figures 9.1.1-9.1.7.

Table 2.2 Radiocarbon and Calibrated dates from each study site.

Study Site	Lab Code	Material	Sample Depth	Radiocarbon Age
Ballinderry Lough	UBA-18585	Plant material	30	1678±30
	UBA-18585	Plant Material	50	1690±26
	UBA-18586	Plant Material	70	1665±30
	Beta-262245	Plant Material	91	1170±40
	Beta-276633	Sphagnum moss	136	1240±40
	Beta-262246	Moss and twigs	148	1080±40
	UBA-17090	Plant Material	149	3039±32
	UBA-17091	Plant Material	178	1162±39
	UBA-17444	Plant Material	199	1535±21
	UBA-17444	Organic/seeds	209	1535±21
	UBA-19054	Plant Material	241	1547±36
	UBA-17445	Plant Material	268	5313±31
	UBA-19055	Plant Material	273	3499±25
	Beta-262247	Wood	289	9240±50
Borheen Lough	Beta-173455	Bulk Sediment	400	3260±40
	Beta-173466	Bulk Sediment	510	4690±40
	Beta-173467	Bulk Sediment	785	10230±50
	Beta-182359	Bulk Sediment	100	1140±40
	Beta-182396	Bulk Sediment	225	1570±40
	Beta-182397	Bulk Sediment	600	6410±40
	Beta-182398	Bulk Sediment	700	9020±50
	Beta-182399	Bulk Sediment	820	10560±50
Cornaher Lough	Beta-95516	Betula fruits	406	4210±60
	Beta-95517	Betula fruits	478	5710±60
	Beta-95518	Prunus fruit stones	523	8400±60
Cuckoo Lough	UBA-26986	Bulk Sediment	56	1164±33
	UBA-23832	Bulk Sediment	153	4434±35
	UBA-23833	Bulk Sediment	363	12809±70
	UBA-26987	Bulk Sediment	366	2219±45
	UBS-26988	Bulk Sediment	468	6074±46
	UBA-26989	Bulk Sediment	521	8013±56
	UBA-26990	Bulk Sediment	577	9816±70
	UBA-26991	Bulk Sediment	645	14330±83
Kelly's Lough	Beta-17342	Bulk Sediment	100	1620±40
	Beta-165539	Bulk Sediment	164	1360±40
	Beta-173462	Bulk Sediment	245	2520±40
	Beta-165540	Bulk Sediment	294	4600±50
	Beta-165541	Bulk Sediment	334	5430±50
	Beta-165542	Bulk Sediment	369	6480±50
	Beta-173463	Bulk Sediment	410	8220±50
	Beta-165543	Bulk Sediment	459	8970±60
	Beta-173464	Bulk Sediment	485	9610±40
Diheen Lough	Beta-173458	Bulk Sediment	44	1190±40
	Beta-173459	Bulk Sediment	120	740±40
	Beta-173460	Bulk Sediment	176	890±40
Doo Lough	Beta-124766	Bulk Sediment	828	2250±70
	Beta-124767	Bulk Sediment	942	3550±80
	Beta-124768	Bulk Sediment	978	4590±60
	Beta-124769	Bulk Sediment	1058	7010±50
Sheheree Lough	Beta-124771	Bulk Sediment	203	1470±70
	Beta-124772	Bulk Sediment	246.5	3350±70
	Beta-124773	Bulk Sediment	314	3730±70
	GrN-22075	Bulk Sediment	365.5	3800±60
	GrN-22076	Bulk Sediment	419	3980±80
	GrN-22077	Bulk Sediment	447	7930±70

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Chapter 3

Study Sites

3.1 Introduction

This chapter provides information on all seven study sites used in this project. The sites were selected based on the availability of the data, their location and the nature of the sediment i.e. lacustrine material. They give a regional spread across Ireland and Figure 3.1 below shows the location of all seven sites within Ireland. The sites are discussed in terms of four geographical location; The Irish Midlands (Ballinderry and Cornaher Lough), Killarney National Park (Cuckoo and Sheheree Lough), The Galty Mountains (Borheen and Diheen Lough) and The Wicklow Mountains (Kelly's Lough). Table 3.1 gives a summary of the characteristics of each study site.



Figure 3.1 Map showing all the study sites

Table 3.1 Summary table of study site characteristics

Study Site	Co-ordinates	Location	Elevation	Geology	Lake Size	Water Depth	Core Length	Time Period
Ballinderry	Latitude:53°24'6.01''N Longitude:07°40'34''W	Irish Midlands	80m	Carboniferous Limestone	1.30ha	2.7m	3.00m	0-10650BP
Borheen	Latitude:52°22'20''N Longitude:08°09'08''W	Galty Mountains	476m	Old Red Sandstone	2.45ha	6.7m	8.30m	0-12640BP
Cornaher	Latitude:53°21'47''N Longitude:07°24'48''W	Irish Midlands	91m	Carboniferous Limestone	0.24ha	1.86m	6.88m	0-11500BP
Cuckoo	Latitude:52°00'09.0''N Longitude:09°33'34.2''W	Killarney National Park	32m	Old Red Sandstone	0.15ha	2.65m	6.52m	0-17500BP
Diheen	Latitude:52°22'09''N Longitude:08°10'15''W	Galty Mountains	554m	Old Red Sandstone	0.79ha	5.4m	1.76m	0-860BP
Kelly's	Latitude:52°57'17''N Longitude:06°25'45''W	Wicklow Mountains	585m	Granite	3.0ha	8.6m	1.60m	0-11100BP
Sheheree	Latitude:52°2'27''N Longitude:09°28'49''W	Killarney National Park	65m	Carboniferous Limestone	1.96ha	Site Infilled	6.12m	0-10500BP

3.2 Irish Midlands

Ballinderry Lough (Latitude: 53°24'6.01"N Longitude: 07°40'34"W) is located near the border of County Offaly and County Westmeath in the Irish midlands. It is on the border between the townlands of Ballinderry, parish of Kilcumreragh, and Kilnahinch, parish of Kilmanaghan, both of which are in the barony of Clonlonan (Johnston, 1999). The Lough is located 2.64km east of the town of Moate and approx. 1.8km north of the N6 routeway. Cornaher Lough (Latitude: 53°21'47"N Longitude: 07°24'48"W) an adjacent site lies approx. 9km to the east of Ballinderry Lough, 3.2km west of Tyrellspass village and 4.8km east of Kilbeggan in Co. Westmeath. Figure 3.2.1 shows Ballinderry Lough on the day of coring.



Figure 3.2.1 Ballinderry Lough on the day of coring

Ballinderry Lough is a single small lake at an elevation of 80m. The maximum depth of the lake was recorded via a bathymetric survey to be 2.7m. The first metre of the lake sediment was removed using a Perspex tube, while the remaining sediment was collected using a Livingstone piston corer, resulting in two sediment cores of 4 and 3 metres (O'Carroll, 2012). Cornaher Lough is a small eutrophic lake approx. 25m radius, covering an area of approx. 0.24ha. Figure 3.2.2 shows the aspect facing east from Cornaher Lough. Two cores were taken from the deepest point

of Cornaher Lough (1.86m) also using a Livingstone piston corer and they extended to depths of 6.88m and 6.5m (Heery, 1998).

The landscape surrounding these sites is low-lying and dominated by peatlands and eskers. Cornaher Lough lies approx. 140m south-east of one such esker, namely Long Hill esker, and has one natural inflowing stream from the surrounding land which is intensively grazed for dairy and sheep farming. The eskers influence the character of the soils in the area which can be characterised as lime-rich grey brown podzolics, which are well drained, possess a high pH and have a high Calcium Carbonate content. This type of soil is generally considered to be a valuable all-purpose soil, suitable for agricultural practices. The underlying geology of the area is dominated by Carboniferous limestone overlain by intermittent glacial features. The soil in the surrounding area is high in luvisols and cambisols (IV). It is a soil with a clay-enriched lower horizon, high cec, and a high saturation of bases.



Figure 3.2.2 Cornaher Lough, Co. Westmeath, facing east.

The landscape surrounding Ballinderry and Cornaher Lough is cultivated, with some natural vegetation preserved, consisting dominantly of marsh land, open grassland and *Salix* (willow). The wider landscape is dominated by species such as *Corylus avellana* (Hazel) and *Fraxinus excelsior* (Ash). Other tree species which occur are *Ulmus glabra* (Wych Elm), *Quercus robur* (English Oak) and occasionally *Sorbus hibernica* (Irish

Whitebeam). Immediately adjacent to the lakes is a thick reedswamp with numerous emergent plants, consisting of *Phragmites australis* (Common Reed) and *Typha latifolia* (Bulrush) also *Glyceria maxima* (Reed sweetgrass) and *Carex riparia* (Greater pond sedge), which are generally restricted to eutrophic waters. The rich flora and fauna of lakes is reflected in their eutrophic state, with characteristic free-floating aquatic plants such as *Lemna trisulca* (Star Duckweed), *Hydrocharis morsus-ranae* (Frogbit) and *Stratiotes aloides* (Water soldier), and these are all indicators of rich alkaline conditions. They also contain a number of submerged species such as *Potamogeton pectinatus* (Fennel pondweed) and several other species of pondweed (Heery, 1998). There is a significant diversity of flora and fauna found here which is likely to be mirrored in the palaeoecological record for the area.

The Irish Midlands has temperate cold and warm seasons, and temperatures do not differ much between day and night (~0.5°C). The maximum value for mean daily air temperature in summer is ~19°C while in winter, the mean minimum temperature is ~2.5°C. Annual rainfall in the area is among the lowest in Ireland and has fluctuated between 960mm and 1200mm between 2012-2015 (www.met.ie)

From the study of cartographic sources one can determine that Ballinderry Lough was once much larger than it is today. It was drained during the construction of the railway line in the 1840s and it is now approximately one third of its original size (Brooks, 2009). Cornaher Lough is also thought to have been much larger during post-glacial times, covering up to 24 hectares and reaching depths of 12-15m (Heery 1998). The size of the lough was further reduced during the 1940s and 1950s due to the Westmeath arterial drainage scheme.

There are a wide range of archaeological sites in the landscape surrounding Ballinderry and Cornaher Lough, which reflect approx. 6,000 years of human activity in the area. Figure 3.2.3 shows the archaeological sites surrounding Cornaher and Ballinderry Lough in the Irish Midlands.

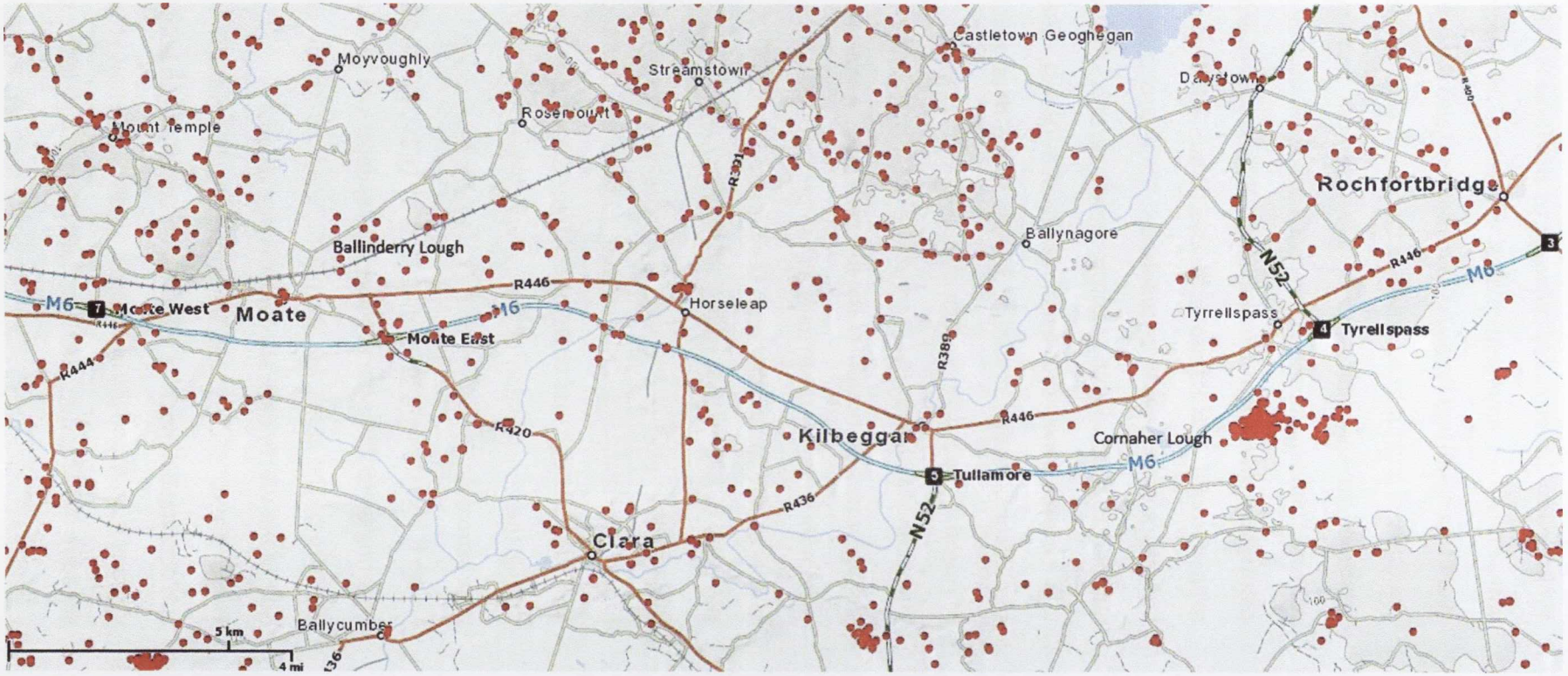


Figure 3.2.3 Archaeological sites surrounding Ballinderry and Cornaher Lough, Co. Westmeath (www.archaeology.ie)

Most of these sites were revealed during the construction of the N6 Kinnegad to Athlone road scheme, when excavations were undertaken by four different archaeological companies (O'Carroll, 2012). As well as these there is a large volume (over 800) of sites known from the record of monuments and places database (www.archaeology.ie). These contain over 35 site types spanning a wide range of time periods from the prehistoric to early medieval and bronze age, including but not limited to barrows, cairns, standing stones, ringforts, soutterains, tower houses and churches. One of the most significant discoveries was that of two high status crannogs which were excavated at the site of this Lough in the 1940s by the Harvard expedition. Ballinderry 2 located at the lakeshore edge was a location for high status settlement with occupation phases dated to the late bronze age and 6th and 7th century AD (Hencken, 1942, Newman, 2002, Newman, 1997). The second crannog, Ballinderry 1 dates to 10th and 11th Century AD (Hencken, 1936, Johnston, 1999). Discussion by Johnston suggests a possible abandonment of these sites as Ballinderry lough water level rose (Johnston, 1999). Charcoal pits in the area reached their pinnacle of use in the 9th-11th centuries and could have provided the inhabitants of the Ballinderry crannogs, with a supply of charcoal to fuel their metal working activities, and may be represented in the charcoal records from these lakes.Archaeological sites directly adjacent to Cornaher Lough include ringforts, barrows, a church and graveyard, a standing stone and tower house (www.archaeology.ie). An Anglo-Saxon crannog was unearthed at Newtonlow (N379 369) just North of Cornaher Lough in 1982, and was dated to c.10000 AD (Bourke, 1984). Amongst the artefacts were 30-40,000 animal bones, bone combs, an iron ladle and Anglo-Saxon coins. The finds are typically associated with those of high status, suggesting that the crannog belongs to that of an aristocratic family, who traded with communities in Britain (Mitchell, 1997, Kelly, 1994).

3.3 Galty Mountains

Borheen Lough (Latitude: 52°22'20"N Longitude: 08°09'08"W) and Diheen Lough are small corrie lakes located within cirques in the Galty Mountains, previously formed through Quaternary glacial and periglacial action. Borheen Lough lies at an altitude of 476m, covering an area of 2.45ha and has a sediment core extending 8.3m in depth. Figure 3.3.1 shows Borheen Lough in the Galty Mountains. Diheen Lough lies approx. 1km to the west of Borheen Lough in an adjacent catchment, the two are separated by Galteebeg peak (799 m altitude) (Leira, 2010). Lough Diheen lies at an altitude of 554m and covers 0.79ha, a shorter sediment core of 1.76m was extracted from the lake using a Livingstone corer (Leira, 2010., Livingstone, 1955). Figure 3.3.2 shows Diheen Lough in the Galty Mountains. The Galty Mountains are one of the highest mountain ranges in Ireland. They form an east-west ridge covering 22 km which rises steeply to an altitude of 919m at its highest point. The surface bedrock is Devonian conglomerates and Old Red Sandstone which overlies a core of Silurian shales. The area is dominated by podzols which give way to peaty podzols as altitude increases, with a peat plateau occupying the summit above the Loughs (Leira, 2010).



Figure 3.3.1 Borheen Lough in the Galty Mountains

Annual precipitation at weather stations within 10 km of the lakes is around 1,200mm but these stations lie at altitudes of 150m and so are considerably lower than the lakes. Annual air temperature at these lower altitudes is 10°C. The closest synoptic weather station to the site is at Cork Airport and data from this station has been obtained from the Met Eireann website (www.met.ie). Annual rainfall here has fluctuated between 1130mm and 1250mm between 2012-2015. Winds are predominantly from the west, with an average wind speed of 11.1 knots, and there is an annual average of 16.4 days with snow or sleet recorded at this station.



Figure 3.3.2 Diheen Lough, Galty Mountains

Surrounding Borheen and Diheen Lough, within the Galty Mountains there are 22 archaeological sites, which are largely located to the east of Borheen Lough, and at an elevation ≤500m. The sites are recorded by the National Monuments Service and are classed as 19 cairns, 2 structures and 1 house (www.archaeology.ie) displaying significant human activity in the area. Figure 3.3.3 shows the archaeological sites surrounding Borheen and Diheen Lough within the Galty Mountains.

The Galty Mountains are designated as a Special Area of Conservation (SAC) by the National Parks and Wildlife Service, and contains the following habitat types; European dry heath, alpine and boreal heath,

Nardus grassland, Calcareous rocky slopes, Siliceous rocky slopes and some areas of localised blanket bog on the upper slopes. The bogs are confined to flatter areas along and beside ridge tops and contain species such as *Sphagnum* spp. (Bog mosses), along with *Eriophorium angustifolium* (Common Cottongrass), *Calluna vulgaris* (Heather) and *Carex bigelowii* (Stiff Sedge). The area supports several notable arctic-alpine species that are otherwise rare in Ireland. These include *Cardaminopsis petraea* (Northern Rock-cress), *Oxyria digyna* (Mountain Sorrel), *Rhodiola rosea* (Roseroot), *Saussurea alpine* (Alpine Saw-wort) and *Saxifraga rosacea* (Irish Saxifrage). There are several fern species recorded, most notably *Cystopteris fragilis* (Brittle Bladder-fern), *Hymenophyllum wilsonii* (Wilson's Filmy-fern), *H. tunbrigense* (Tonbridge Filmy-fern) and *Asplenium viride* (Green Spleenwort). The areas of dry heath are dominated by *Calluna vulgaris* (Heather) and *Vaccinium myrtillus* (Bilberry). The upland grassland is species rich and includes the rare species *Pseudorchis albida* (Small-white Orchid), with the main grass species present being *Agrostis capillaris* (Common Bent) and *Nardus stricta* (Mat-grass), while the main sedges are *Carex binervis* (Green-ribbed Sedge), *C. panacea* (Carnation Sedge) and *C. pilulifera* (Pill Sedge). Herb species include *Galium saxatile* (Heath Bedstraw), *Potentilla erecta* (Tormentil), *Pedicularis sylvatica* (Lousewort), *Polygala serpyllifolia* (Heath Milkwort) and *P. vulgaris* (Common Milkwort). Heath species such as *Calluna* (Heather) and *Danthonia decumbens* (Heath-grass) are also found. Over-grazing by sheep, frequent burning, afforestation and hill walking are causing potentially serious damage in the area (NPWS, 2005). Six of the habitats discussed are listed in Annex I of the E.U. Habitats Directive, and two of those have priority status. The presence of the rare, scarce and uncommon plant species mentioned above adds greatly to the significance of the Galty Mountain landscape, which will be further reflected in the palaeoecological record.

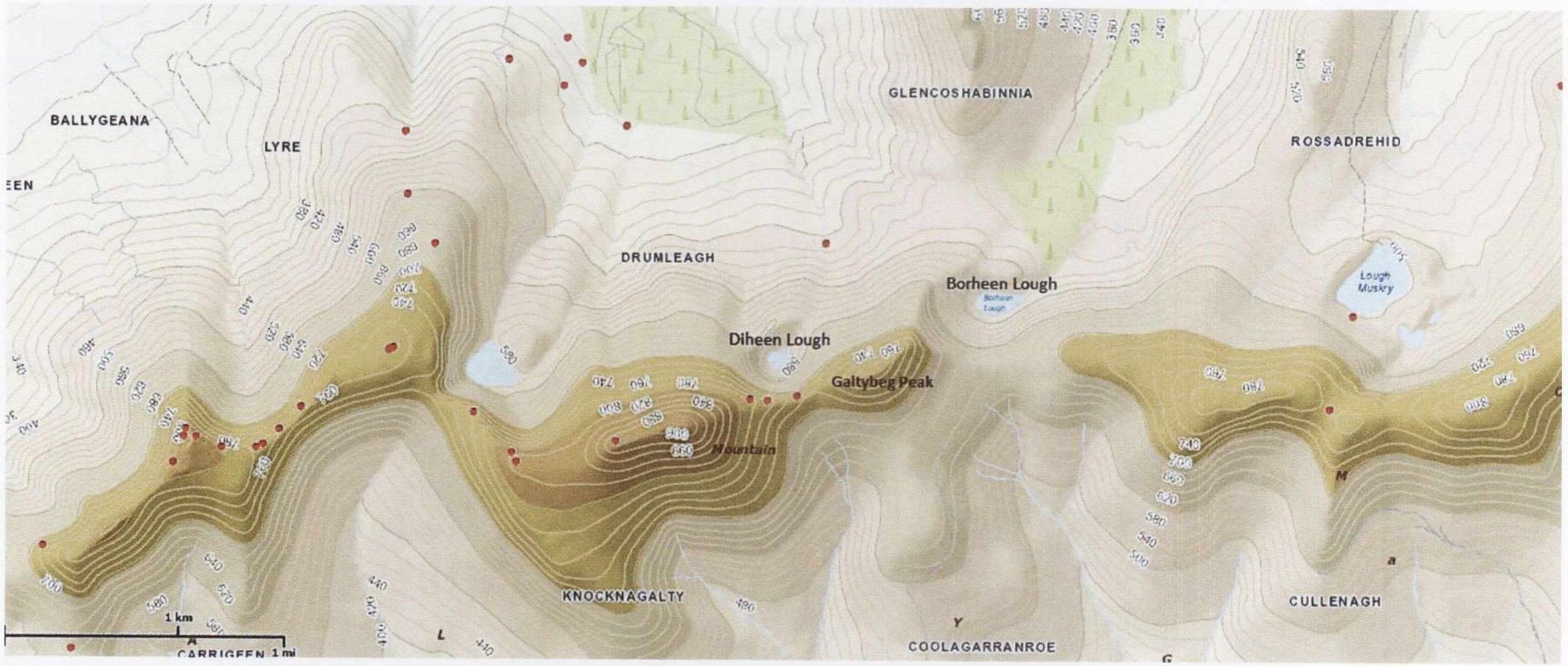


Figure 3.3.3 Archaeological sites surrounding Borheen and Diheen Lough within the Galty Mountains (www.archaeology.ie)

3.4 Killarney National Park

Cuckoo Lough (Latitude 52°00'25"N Longitude 09°55'95"W) a small circular lake, is located in the townland of Glena within Killarney National Park in Co. Kerry. It is approx. 0.8km south west of Dinish Island, Muckross Lake and O'Sullivan's punch bowl, and lies between Shehy Mountain to the North West and Torc Mountain to the south east. Figure 3.4.1 shows Cuckoo Lough within Killarney National Park. The lake is approx. 0.15ha in size and has a maximum water depth of 2.65m, located at an elevation of 32m. A surface core of 1m was extracted from the lake using a Perspex tube and extruded on site at 1cm intervals. A further two overlapping sediment cores were extracted using a Livingstone piston corer, and extended to a maximum depth of 6.52m.



Figure 3.4.1 Cuckoo Lough, Killarney National Park.

Another site Sheheree Lough (Latitude 52°2'27"N Longitude 9°28'49"W) is located within Killarney National Park, and is located within Killarney valley, approx. 4km East of Ross Island in the townland of Sheheree. Figure 3.4.2 shows Sheheree Lough within Killarney National Park. The Lough lies at an altitude of 65m and has an area of approx. 1.96ha. This site is now bogland which established approx. 2000 years ago replacing the former lake. Two overlapping cores were extracted from Sheheree

Lough using a Livingstone piston corer, and extend to a maximum depth of 6.12m (Mitchell et al., 2004)

Killarney National Park is made up of two distinct types of geology, Carboniferous limestone to the north forming the flatter lowland, and Devonian Old Red Sandstone in the south where Cuckoo lough is located, forming the upland region. Sheheree Lough lies within the Carboniferous Limestone region to the North. This contrasting geology has a profound impact on the topography as well as the vegetation (Quirke, 2001). The Killarney landscape was formed by glacial action more than 17,500 years ago, and the Killarney valley was covered by an ice cap that extended as far north as Castlemaine during the final stages of the last glaciation (Thorn, 2001, Warren, 1977). By 13,000BP most of Ireland was free of ice and evidence of plants species can be seen in Late Glacial and Early Holocene records. The underlying geological diversity of Killarney National Park, the range of altitudes, and the influence of the Gulf Stream here provide a varied ecology and a range of ecosystems, including bogs, lakes, moorland and woodland.



Figure 3.4.2 Sheheree Lough, Killarney National Park

Killarney National Park is best known for its oak woodlands, such as Cahnicaun wood to the south of Cuckoo Lough, dominated by *Quercus petraea* (Sessile Oak), with an understory of *Ilex aquifolium* (Holly). Other

tree species present include *Taxus baccata* (Yew), *Alnus glutinosa* (Alder), *Salix* spp. (Willow), *Fraxinus excelsior* (Ash) and *Betula pubescens* (Downy Birch). The surrounding areas of blanket bog are dominated by species such as *Calluna vulgaris* (Heather), *Ulex gallii* (Western Gorse), *Vaccinium myrtillius* (Bilberry), *Sphagnum pulchrum* (Mosses) and *Cladonia mediterranea* (Lichens) (O'Sullivan, 1991). The habitats and flora surrounding these sites are supported by the oceanic climate which is heavily influenced by the Gulf Stream, experiencing cool summers (15°C July average) and mild winters (6°C February average), with a difference of ~2°C between the sites Rainfall is frequent throughout the year, with a mean of 126cm per year (Mitchell et al., 2004).There are few archaeological sites directly adjacent to Cuckoo Lough, the nearest sites are approx. 0.8km to the north east and are a bridge and quay (www.archaeology.ie). Figure 3.4.3 shows the archaeological sites surrounding Cuckoo and Sheheree Lough within the Killarney Valley. There are a number of sites in the surrounding landscape (approx. 3km radius), on the shore of Muckross lake there are 3 copper mines, a country house, a bridge and a metalworking site. To the south west of Cuckoo lough and to the south of Torc mountain, there is a settlement site and field system from circa 18th century which are now abandoned, there is also a building and a lime kiln site nearby. Both sites are adjacent to Ross Island which has been a major site for mining activity (O'Brien, 2004) starting in the Late Neolithic/Copper Age and ending with large-scale industrial operations in the early 19th Century. The method of mining used at Ross Island was known as fire-setting and is generally considered to have involved the consumption of large amounts of wood (O'Brien 1994). It would be expected that this activity would have a significant impact on the surrounding landscape and vegetation. A small monolith (50cm) extracted approx. 1km from the mining site on Ross Island indicates an abrupt but long term vegetation change that may be due to the disturbance in local hydrology caused by mining. The results from Cuckoo and Sheheree Lough are discussed in subsequent chapters,

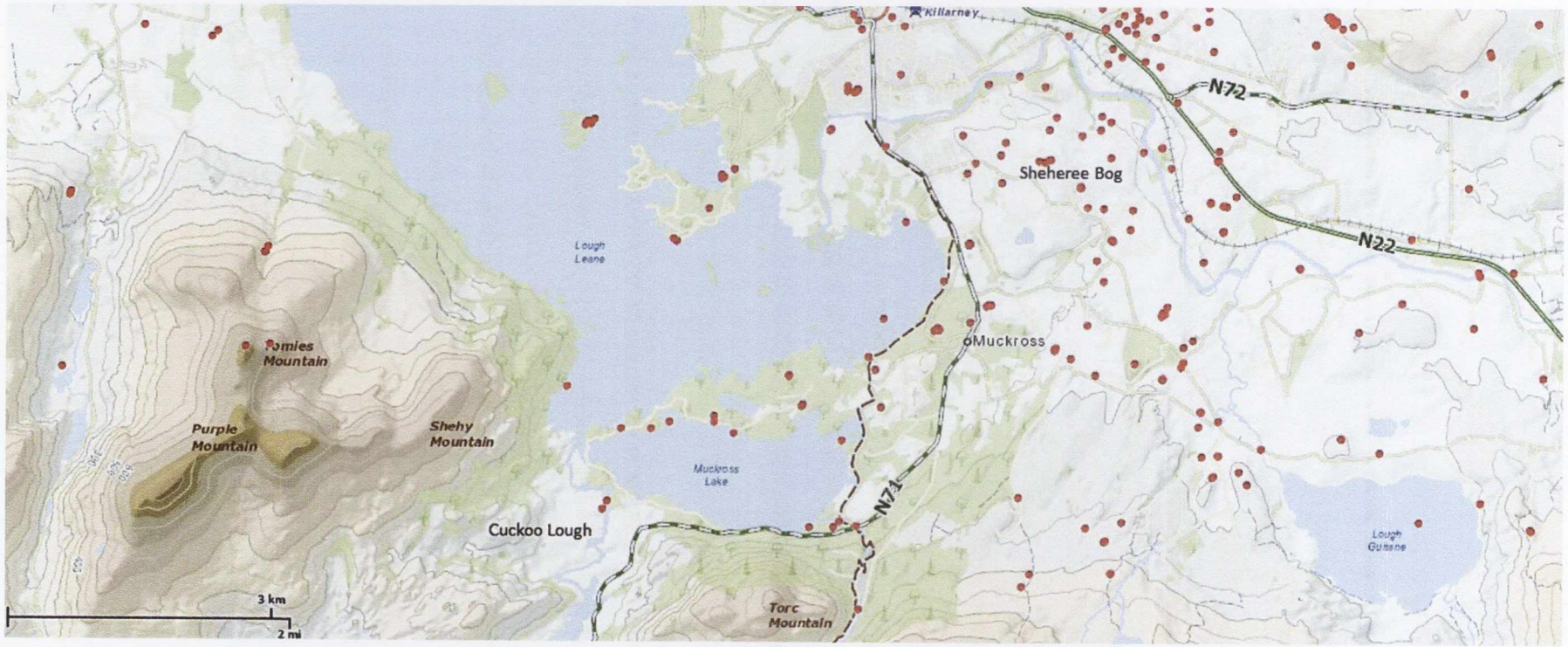


Figure 3.4.3 Archaeological sites surrounding Cuckoo and Sheheree Lough, Killarney National Park (www.archaeology.ie).

however it is possible that such significant anthropogenic activity in the surrounding area had an impact on the vegetation and charcoal records from these sites. A larger number of archaeological sites are located within the Killarney Valley, confining these to a 2km radius around Sheheree Lough, there are 13 Raths, 6 standing stones, a rock scribing, a country house, field boundaries, a religious house belonging to the Franciscan Friars and a children's burial ground in the form of a Cashel (www.archaeology.ie). These sites range in time period from the Iron Age to the present day, the large number of raths would suggest that there was significant anthropogenic activity in the landscape during the Early Middle Ages, which would coincide with the Early Medieval mining activity at Ross Island. The sediment record from Sheheree Lough is likely to have preserved evidence of this anthropogenic and mining activity adjacent to the site from the Late Neolithic to the present day, the results of which are discussed later.

3.5 Wicklow Mountains

Kelly's Lough (Latitude 52°57'17"N Longitude 06°25'45"W) is located in the east of Ireland within the Lugnaquilla Complex, an extensive upland area in the Wicklow Mountains. Figure 3.5.1 Shows Kelly's Lough within the Wicklow Mountains. Lugnaquilla Mountain stands in the middle of the complex and at 925 m is the highest mountain in Wicklow.

The Wicklow Mountains are part of a larger granitic mass, which extends all the way from Dun Laoghaire to New Ross, forming the largest mass of granite *(batholith)* in North Western Europe. Over millennia ice sheets and storms have eroded away much of this rock to form the mountains we see today (Farrington, 1934). Lugnaquilla Mountain mentioned previously is among one of the few places where some of the original schist remains.



Figure 3.5.1 Kelly's Lough, Wicklow Mountains

Kelly's Lough is a small, elliptical dark water cirque lake. It is located at 585m above sea level, has a maximum depth of 8.6m and an area of approx. 3 hectares. A surface core of 110cm in length was extracted from the lake using plexiglass, and a further two overlapping cores were extracted using a Livingstone piston corer, extending to a depth of 507cm (Leira, et al., 2007). The bedrock surrounding Kelly's Lough is predominantly granite bordered by schist and slates. The most extensive soil types are dominated by peat (up to 2m in depth) with blanket bog covering the uplands (Leira et al., 2007). Blanket bogs are ombrogenous mires that are typical of upland areas where rainfall is high (Lowe and Walker, 1997). They have developed during the mid-to-late Holocene as a result of some combination of climatic deterioration, soil retrogression and possibly human impact (Roberts, 1998). The main factor that appears to determine the extent of blanket mire in an area is the climatic humidity, expressed in terms of precipitation/evaporation ratio (Moore, 1993). Organic matter accumulates in peat due to low decomposition rates as a result of waterlogging and anoxia (Malmer 1992). High water tables are a key characteristic and are maintained by sustained precipitation and poor drainage i.e soil retrogression. This reliance on precipitation makes blanket bogs sensitive to changes in climate and they tend to be associated with climate deterioration, characterised by increased wetness (Coll et al., 2014). Blanket bogs require specific

conditions and take thousands of years to form, and are therefore of high conservation value. Largely as a result of bog-cutting and human impact only ~28% of blanket bogs in Ireland remain in a relatively intact condition (Malone & O'Connell 2009). Sheep grazing and afforestation are the main form of land-use here, although there is no afforestation above the lake (Leira et al., 2007). The vegetation is a mix of blanket bog species, heath and upland grassland dominated by *Calluna vulgaris* (Heather), *Nardus stricta* (Matgrass) and *Eriophorum* (Cottongrass) species (Leira et al., 2007). Other species in the landscape include ferns such as *Cryptogramma crispa* (Parsley Fern), *Dryopteris carthusiana* (Narrow Buckler Fern) and *Pteridium aquilinum* (Bracken). Graminoids such as *Carex echinata* (Star Sedge), *Juncus effusus* (Soft Rush) and *Trichophorum cespitosum* (Deer-grass). Herbs such as *Viola palustris* (Marsh Violet), *Saxifraga hypnoides* (Mossy Saxifrage) and *Ranunculus acris* (Meadow Buttercup). Shrubs such as *Empetrum nigrum* (Crowberry), *Hedera helix (*Ivy), *Myrica gale* (Bog Myrtle) and *Rhododendron ponticum* (Rhododendron). And finally tree species such as *Pinus sylvestris* (Scot's Pine), *Larix decidua* (European Larch), *Pseudotsuga mensziesii* (Douglas Fir) and *Salix* spp. (Willow) (NPWS, 2013). The Wicklow Mountains have been designated as a Special Area of Conservation (SAC) due to the unique species diversity and the range of habitats, including; Oligotrophic to Mesotrophic Standing Waters, Dystrophic Lakes, Wet and Dry Heath, Alpine and Subalpine Heaths, Species-rich Nardus Grassland, Blanket Bogs, Siliceous Scree, Calcareous Rocky Slopes, Siliceous Rocky Slopes and Old Oak Woodlands (NPWS, 2013). The climate at Kelly's Lough is mild with mean daily temperature ranging from averages of 1° C in January to 13° C in July. Average annual rainfall in these upland areas ranges from 1,300 to 2,400 mm and increases with altitude. The number of rain days varies between 175 and 200 (>0.2 mm) per year. Precipitation is highly influenced by airborne sea salts, but their proportion decreases eastwards (Aherne and Farrell, 2002).

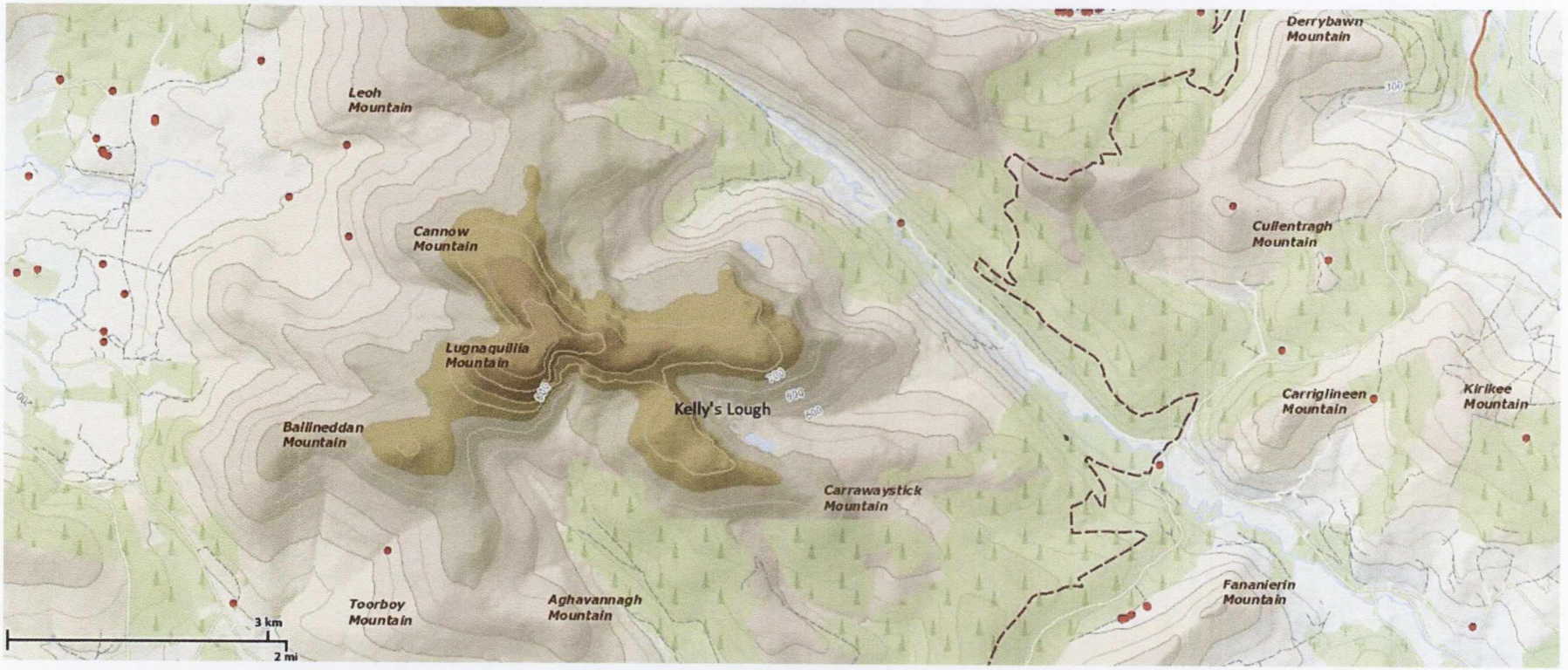


Figure 3.5.2 Archaeological sites surrounding Kelly's Lough, Wicklow Mountains (www.archaeology.ie).

Archaeological sites within a 7m radius of Kelly's Lough include 3 enclosures, 3 hut sites, 3 standing stones, 2 ringforts, a cairn, a burial site and an ecclesiastical site (www.archaeology.ie). In the wider landscape of the Wicklow Mountains there is a wealth of archaeology, including a number of passage and wedge tombs which are up to 5,000 years old. There are also areas of ironworking activity, charcoal production and ancient cooking places, 'Fulachta Fia', represented on the landscape by small mounds. Figure 3.5.2 shows the archaeological sites surrounding Kelly's Lough in the Wicklow Mountains. Humans were active adjacent to Kelly's Lough from the Neolithic through the Bronze Age and into modern times. This will be further reflected in the palynological and charcoal records discussed later.

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Chapter 4

Identifying Past Fire Regimes in Ireland throughout the Holocene

Abstract

Globally, in recent years there has been an increase in the scale, intensity and level of destruction caused by wildfires. This can be seen in Ireland where significant changes in vegetation, land use, agriculture and policy, have promoted an increase in fires in the Irish landscape. This study looks at wildfire throughout the Holocene and draws on palaeolimnological records from seven sites spread across Ireland. Macroscopic charcoal analysis from lacustrine sediment has been widely used to infer spatially explicit reconstructions of past fire regimes. A number of techniques are used here utilising the charcoal record, to reconstruct specific fire events and their magnitude, fire frequency and fire return intervals. Building up a picture of the past fire regimes that existed in Ireland throughout the Holocene. The results are then analysed using three statistical tests to examine if the records are appropriate for peak detection and if the identified charcoal peaks are associated with significant fire events. A varying number of fire events are identified at each study site and help to provide a critical view of current charcoal analysis methods.

4.1 Introduction

Lakes represent one of the best archives for palaeoenvironmental information, and palaeolimnology i.e. the study of past conditions and processes in lakes, is now a well-established and constantly evolving discipline (Last et al., 2001). Analysis of lake sediments can be traced back

to the 1920s when Lundquist (1927) and Nipkow (1927) were conducting studies to classify and describe laminated sediments. By the 1940s considerable work had been carried out using lake sediment stratigraphies to test ideas about classification and the natural evolution of lakes, by Hutchinson (1940) in the USA and Pennington (1943) in the UK. Over the following decades palaeolimnologists began to ask further questions about lake sediment, with regards to their nature and evolution, their geochemistry and how the sediment is impacted by anthropogenic factors, pollution, climate and processes occurring within the lake catchment (Hasler, 1947, Deevey, 1955, Haworth, 1969, Bradbury, 1975). At present there is an ever-increasing range of techniques and analytical methods available, making it possible to produce high quality environmental reconstructions at a high temporal resolution, which are of great importance to address many theoretical and practical questions in palaeolimnology (Cohen, 2003, Smol, 2009, Batterbee et al., 2012).

Lake sediments hold the key to multi-proxy studies which are becoming increasingly common in palaeolimnology, these proxies include but are not limited to pollen grains, charcoal fragments, plant macrofossils, chrominids, diatoms, phytoliths and soil geochemistry, which are used to reconstruct the character of the past landscape, past climatic conditions, catchment processes and identify extreme events occurring within the surrounding landscape (Smol, 2009, Birks and Birks, 2006, Michelutti and Smol, 2013). Lake sediments accumulate continuously over time and it is important to produce a reliable chronology to set the multi-proxy data in the right context. Most sedimentary records are homogenous without any pronounced annual layers, and are commonly dated using radio-isotopic methods such as carbon and lead (Hajdas, 2006, Cook and van der Plicht, 2013). Lake sediments can therefore be seen as one of the best archives for palaeoecological data, providing a wide variety of

proxies which can be used and dated to produce a reconstruction of the past environment (Douglas, 2013).

Charcoal fragments deposited in lake sediments are used to reconstruct long-term variations in fire occurrence, and are often interpreted in conjunction with pollen grains and archaeological sites, to examine the linkages among climate, vegetation, fire and anthropogenic activity (Whitlock and Larsen, 2001). Pollen-slide charcoal studies were popular since the work of Iversen (1941), with smaller charcoal fragments reflecting a regional source area. The analysis of larger charcoal fragments began with pioneering studies such as Clark (1988), Patterson et al. (1987) and Long et al. (1998), and began to address questions related to the theory of charcoal analysis and issues such as source area, deposition and sampling. Since these there have been great advances in the interpretation and analysis of charcoal particles, with a set of standard methodologies becoming widely accepted for the various types of charcoal analysis. Charcoal can be divided into two categories; Macro-charcoal (>125µm) and Micro-charcoal (<125µm), which are analysed using two different techniques. Micro-charcoal, prepared through standard pollen preparations (Pearsall, 1989), is identified and counted on pollen slides under a transmitted light microscope. Whereas macro-charcoal is prepared using a unique process involving a solution of sodium hexametaphosphate, sieving and bleach (Stevenson and Haberle, 2005). A petri dish of charcoal is produced which can then be counted visually under the microscope, or via a digital image analysis in a programme such as image J (Abràmoff, 2004). These analyses can produce charcoal count and charcoal area values at a high temporal resolution which are used in subsequent data analysis to reconstruct patterns of fire history. Reconstructing fire history depends upon an understanding of the processes controlling wildfires, their ignition, spread and subsequent charcoal accumulation. Over recent decades studies have been carried out which greatly contribute to the

understanding of the processes involved and have helped identify key assumptions concerning charcoal dispersal and taphonomic processes (Clark et al., 1998, Blackford, 2000, Mohr et al., 2000, Carcaillet, 2001, Lynch et al., 2004, Whitlock and Bartlein, 2004, Higuera et al., 2005). The interpretation of fire history from sediment charcoal rests upon three of these assumptions. Firstly, it is accepted that the majority of macroscopic charcoal falls close to its source, meaning that any peaks in sedimentary charcoal represent "local" fires (Clark, 1988). Studies matching charcoal peaks to known fire events have supported this assumption and defined "local" as a spatial scale of up to several hundreds of meters (Lynch et al., 2004, Higuera et al., 2005, Higuera et al., 2007). The subject of dispersal distance is complex as various studies have shown charcoal travelling tens of kilometres (Tinner et al., 2006) with other travelling less than one hundred meters (Clark et al., 1998, Ohlson and Tryterud, 2000). A second assumption in interpreting charcoal accumulation is that secondary charcoal deposition via slope wash or within-lake re-deposition does not obscure patterns of primary charcoal deposition, and it remains the dominant signal in charcoal records (Higuera et al., 2007). Finally, interpreting fire occurrence assumes that sediment mixing and sampling provide adequate temporal resolution for detecting local fire occurrence (Whitlock and Larsen, 2001). These studies have led to the development of analytical techniques to interpret fire occurrence from sedimentary charcoal records. An initial step in fire history reconstruction is to select which type of charcoal data on which to base the analysis. Reconstructions based on charcoal area and charcoal count measurements are considered to be broadly comparable (Ali et al., 2009), however this is not always the rule (Leys et al., 2013, Finsinger et al., 2014a). Therefore it is important to carry out a rudimentary correlation analysis (Hauke and Kossowski, 2011) to test the relationship between the two variables. Where there is a high correlation between both records, charcoal area reconstructions are often favoured as the

issue of particle breakage is eliminated. Breakage may occur during laboratory procedure being represented in a higher charcoal count.

A variety of programmes have subsequently been developed to reconstruct past fire regimes, including CHAPS (Bartlein, unpublished software), Charster (Gavin et al., 2006), CharSim (Higuera et al., 2006) and the more recent CharAnalysis (Higuera, 2009a). These programmes are based on the theory of decomposing a charcoal record into a slow varying background and high frequency peak component (Long et al., 1998). Each of the programmes builds upon the increasing knowledge in the area of charcoal analysis and explores the various parameters that control the nature of the charcoal record. The most recent programme CharAnalysis is user defined requiring a specific set of input parameters, including a type of smoother and size of smoothing window. To eliminate the objectivity associated with a user defined interface, a recent technique has been developed using an ensemble member strategy. This replicates the analysis for each type of smoothing method and size of smoothing window, allowing the selection of these parameters to be based on a signal to noise index and goodness of fit (Blarquez et al., 2013). Although the fire history reconstructions produced by programmes such as Charster and CharAnalysis are widely accepted, new techniques are emerging to further validate these analyses. A signal to noise index exists to assess whether a record is appropriate for peak detection (Higuera, 2009a). However this method has also been recently developed providing a more informed calculation of the signal to noise index (Kelly et al., 2011). A further important development in the analysis of fire history is the creation of a charcoal peak screening process. A minimum-count peak screening test (Gavin et al., 2006) can be applied within the CharAnalysis programme to identify whether the charcoal peaks identified are significant. This analysis is more appropriate for charcoal count data, and with the preference of fire history reconstructions being led by charcoal area data a new method of peak

screening has been developed to accommodate this (Finsinger et al., 2014a). The analysis generates bootstrapped samples for each identified charcoal peak, which are used to create a critical threshold of charcoal area. If the identified charcoal peak is higher than this threshold then it is classed as a robust fire event.

It is clear that a variety of methods exist to analyse the charcoal record, and within this chapter I have selected the most recent and relevant methods available to produce an appropriate record of fire within the past landscape. I present a set of methodologies utilising a variety of programmes and packages, to critically assess their efficiency, reconstructing the past fire regimes at a variety of sites throughout the island of Ireland.

4.2 Aims

1. Critically examine and review the most recent methods for macroscopic charcoal analysis.

2. Apply the most recent and appropriate charcoal methods to the data obtained from 7 study sites.

3. Present an accurate reconstruction of Holocene fire activity at each of the 7 study sites.

4.3 Study Sites

In this chapter all 7 study sites are analysed, Ballinderry Lough and Cornaher Lough Co. Westmeath, Borheen and Diheen Lough, Galty Mountains, Sheheree and Cuckoo Lough, Co. Kerry and Kelly's Lough Co. Wicklow. These sites give a reasonably good spread of the country and encompass a range of habitats. The sites were chosen based on the

availability of the data, their location and the nature of the sediment i.e. lacustrine material. A detailed discussion of each of these sites can be found in Chapter 3.

4.4 Methodology

Macroscopic charcoal analysis was carried out on the sediment cores from all sites and the method for preparation is adapted from those described by Mooney and Black (2003) and Mooney and Radford (2001). Samples were prepared on contiguous 1cm intervals and particles were confined to a size greater than 125µm (Whitlock and Larsen, 2001). Digital image analysis using Image J was applied once the samples were prepared, to generate count and area data, and follows methods similar to Schlachter (2012). The digital image analysis differed at Kelly's Lough and Ballinderry Lough where a previous software Scion Image was used (Murphy, 2008, O'Carroll, 2012).

Each of the sediment cores were radiocarbon dated, and a variety of material was used for dating, including bulk sediment, leaf fragments and twigs. A chronology was produced for each site using BChron, a statistical package in R which uses Bayesian models to map radiocarbon dates to calendar ages (Haslett and Parnell, 2008). The Intcal13 calibration curve was used for the Bchron analysis. Table 2.2 in chapter 2 shows all the radiocarbon dates from each of the study sites. The following methods provide a description of the statistical analysis used here to analyse the extracted charcoal data.

4.4.1 Charcoal Area vs. Charcoal Count Analysis

To examine the difference between charcoal count and area reconstructions, charcoal data from each of the study sites were plotted

against one another in a correlation analysis, and a Spearman's Rank Correlation Coefficient calculated (Hauke and Kossowski, 2011). A least-squares regression was used to test the relationship between charcoal counts and areas, with charcoal count as the predictor and charcoal area as the response variable (Finsinger et al., 2014a). Similarly to detect the possible effect of particle breakage, charcoal count/area ratios were plotted against charcoal counts (Leys et al., 2013). Where particle breakage has occurred, it is predicted that in samples which have higher charcoal counts there are higher charcoal count/area ratios (Finsinger et al., 2014a).

4.4.2 Ensemble-Member Strategy

Before beginning the fire history reconstruction an Ensemble-Member Strategy in Matlab is employed (Blarquez et al., 2013). The analysis of a charcoal record requires a series of user defined choices, including the choice of a filtering method for raw Charcoal Accumulation Rate ($Char_{raw}$). As there is no universal $Char_{raw}$ filtering method an ensemble-member strategy can be used which replicates the analysis of a charcoal record using custom smoothing parameters. A modified version of the CharAnalysis software is used, with the five smoothing parameters; Moving Mode (MMo), Moving Median (MM), Moving Average (MA), LOWESS (LOWESS), and Robust LOWESS (rLOWESS). For each smoothing parameter 470 analyses are run using various smoothing windows (t), where t=100,103,..., 1501. For each sedimentary charcoal record, 2350 (470x5) fire event reconstructions are produced. The $Char_{peak}$ component is calculated as a residual series (i.e $Char_{peak}$= $Char_{raw}$-$Char_{back}$) as the focus here is to distinguish between different filtering methods. A locally defined threshold is used to separate the $Char_{noise}$ (background charcoal) and $Char_{fire}$ (peak charcoal) components. These two procedures protect from biases related to variation in both the mean and variance of the

empirical and simulated charcoal series (Higuera et al., 2010). The locally defined threshold is defined based on the C_{peak} distribution within a given number of samples surrounding each sample. The timescale used to define the local threshold is the same one used to define the C_{back}. In the final stage of this analysis the fire return interval (FRI) distributions are modelled and include the mean number of reconstructed fire events, the median FRI value and the Weibull b parameter that is estimated for each filtering method. Fire Frequency (FF) is also calculated for each reconstruction member using a kernel density function (Mudelsee et al., 2004). The median FF and percentiles of the reconstruction ensemble are estimated based on the distribution of all reconstruction members. This analysis aims to remove the objectivity associated with a user defined interface and to select quality fire history reconstructions from a pool of members based on statistical accuracy and rational criteria i.e. signal to noise index and goodness of fit (Blarquez et al., 2013). From this analysis a $Char_{raw}$ filtering method and smoothing window were selected specifically for each study site.

4.4.3 Fire-History Reconstruction

CharAnalysis is used within Matlab and is a set of diagnostic and analytical tools, with the goal of peak detection to reconstruct "local" fire history (Higuera, 2009a). Charcoal data from each study site were loaded into the software via an input file, containing Char area, depth and Age BP. This analysis contains a user defined element and a second input file is required defining parameters such as threshold type, threshold method, age range, smoothing method and peak frequency. The charcoal accumulation rate is calculated to estimate the number of fire events. The charcoal area input, sample volume and depth are interpolated using the median sample resolution. Where appropriate, transformations can be applied to the charcoal data to remove any trend prior to peak

analysis. The $Char_{raw}$ is then divided into two main components $Char_{back}$ and $Char_{peak}$. The $Char_{back}$ is defined by a variety of smoothing methods, selected specifically depending on the nature of the charcoal data generated at each site. The five smoothing parameters are; Moving Mode (MMo), Moving Median (MM), Moving Average (MA), LOWESS (LOWESS), and Robust LOWESS (rLOWESS).The smoothing method used here for each site was predetermined by the ensemble-member analysis. The selected smoothing window was calculated based upon a test between the empirical $Char_{noise}$ values and the modelled $Char_{noise}$ distribution, which provides an index of how well the $Char_{noise}$ model fits the empirical data (Higuera et al., 2009). The charcoal peaks can be defined as a residual ($Char_{peak}=Char_{raw}-Char_{back}$) or as a ratio ($Char_{peak}=Char_{raw}/Char_{back}$), and are defined specific to each site. The associated threshold value that separates $Char_{Fire}$ and $Char_{Noise}$ within the $Char_{Peak}$ component is set at the 95th percentile of a Gaussian mixture model. Except for at Kelly's Lough where the threshold value is based on the 95th percentile of a noise distribution, modelled with 1-mean Gaussian. This distinction was made due to the nature of the data at Kelly's Lough; a variation in the counting method meant that an alternative threshold calculation was necessary to replicate comparable results. Finally identified peaks can be screened using a "minimum count" approach, which calculates the probability that two charcoal values arise from the same poisson distribution. However this analysis is more suitable for charcoal count data. An alternative method of peak screening was also used in the analysis, appropriate for charcoal area data and is discussed in further detail below. The CharAnalysis software identifies specific fire events, their magnitude, the fire return interval and the fire frequency, providing an accurate picture of the fire regime at each site.

4.4.4 Fire Frequency

CharAnalysis calculates fire frequency by summing the total number of fires within a pre-defined window and applies a smoothing technique (Higuera, 2009a). An alternative method of calculating fire frequency is also used here to analyse the records at each study site. This method calculates the palaeo-fire frequency using a Gaussian kernel and computes confidence intervals around this (Higuera, 2012). Input requirements are the dates of fire events, which were defined in this case using the previously described CharAnlaysis method of decomposition and smoothing. Optimal kernel bandwidth for the analysis is calculated using maximum log likelihood. This method provides an accurate fire frequency curve for each study site.

4.4.5 Signal to Noise Index

The Signal to Noise Index (SNI) is a means of evaluating the suitability of sediment–charcoal records for reconstructing local fires. Sedimentary charcoal records are highly variable, both within and between sites, meaning some records are more appropriate for peak detection than others (Power et al., 2008). This is often caused by issues such as sediment mixing or reduced sedimentation rates (Higuera et al., 2007). As discussed above, to reconstruct fire history a macroscopic charcoal record is decomposed into a background and peak series i.e. noise (N) and signal (S) respectively, which are determined via a threshold value (Gavin et al., 2006).The noise here is assumed to be normally distributed and this is the accepted convention (Kelly et al., 2011). The SNI compares the variability in the signal population, var (S), to the variability in the noise population, var (N): SNI=var(S)/var(S)+var(N). This analysis is more sophisticated than standard statistical tests which determine if two populations are distinct. They are of little value as they produce very low

p-values, regardless of the prominence of peaks within the record (Kelly et al., 2011). The SNI is conceptually based on previous tests, but it produces a useful index reflecting the probability that the values in S could be drawn from the same population as N. A SNI greater than 3 consistently identifies records appropriate for peak detection (Kelly et al., 2011). However based on comparisons to a null model, Higuera et al. (2009) proposed that SNI>~0.5 is generally sufficient to warrant peak analysis. The analysis proposed by Kelly (2011) differs from the earlier method proposed by Higuera (2009a) in the way the index is calculated.

The two equations are compared below:

Higuera 2009

$$SNI = \frac{\text{var}(S)}{\text{var}(S) + \text{var}(N)}$$

$\text{var}(S)$
variability in the signal population
$\text{var}(N)$
variability in the noise population

Kelly 2011

$$SNI = \begin{cases} \left(\frac{1}{n_s}\sum_{i=1}^{n_s}\frac{S_i - \overline{N}}{\sigma_N}\right)\left(\frac{n_N - 2}{n_N}\right) & n_s \geq 1 \\ 0 & n_s = 0 \end{cases}$$

n_S samples in population S.
n_N samples in population N
$\{S_1, S_2, \ldots S_{n_s}\}$ are the CHAR values of individual samples in S
$\overline{N}$ and σ_N are the mean and standard deviation

Both analyses were applied to the charcoal data from each study site to assess whether the charcoal records are appropriate for peak detection.

4.4.6 Charcoal-area Peak Screening

CharAnalysis software applies a minimum-count peak-screening test to screen fire peaks identified based on char count. This analysis applies a similar test but one appropriate for charcoal area data. The analysis is carried out in R using a script called ARCO for Charcoal Area Counts (Birks et al., 2012, Blaauw, 2010). This method screens charcoal area peaks

identified through the CharAnalysis programme to guard against interpreting potential insignificant peaks as fire episodes. A distribution of simulated charcoal areas was obtained by generating bootstrap samples for each identified $Char_{area}$ peak and summing the particle areas within each sample. The bootstrapping is used to obtain the range of likely $Char_{area}$ for previously identified peak samples. The bootstrapped charcoal-area measurements were simulated by random sampling (with replacement) from distributions of observed areas of individual charcoal particles. The sampling distribution is restricted to particles from samples within a user-defined window (i.e. 1000 years) centred on each peak to be screened. Significant charcoal-area peaks were then defined as those that had a C_A higher than the pth percentile threshold of the bootstrapped values. In this analysis, we used $p = 0.95$, but as for the minimum-count test (Gavin et al., 2006) discussed previously, this threshold can be changed where appropriate to adjust the sensitivity of the screening. Peaks with total area within the likely range of bootstrapped samples (e.g. $p > 0.05$) are flagged as potentially unreliable, whereas samples with total area significantly greater than expected by chance are deemed robust indicators of past fire events. To determine the influence of charcoal-particle areas on the $Char_{area}$-based fire-episode reconstruction, charcoal-particle areas of the screened and unscreened samples are compared i.e. the simulated charcoal areas are compared with the actual measured C_A to detect potentially insignificant peaks (those with a charcoal area that could be obtained easily by chance), which may then be removed to obtain a new local-fire-episodes reconstruction (Finsinger et al., 2014a). This analysis reinforces the identification of the charcoal area peaks with a valid and tested statistical method, and is applied to the charcoal data from each study site.

4.5 Results

4.5.1 Charcoal Area vs Charcoal Count Analysis

The relationship between area and count charcoal data was investigated at all sites using a Spearman's Rank Correlation Co-efficient. The results supported similar previous analysis that reported strong correlations between the area and number of charcoal particles (Finsinger et al., 2014a, Ali et al., 2009, Carcaillet et al., 2007, Tinner and Hu, 2003). The Spearman's Correlation analysis returned Rho values ranging from 0.636 at Cuckoo Lough to 0.980 at Cornaher Lough, with p-values less than 0.0001, indicating that there was a significant positive correlation at each of the study sites between the charcoal area and count data. A least-squares linear regression was also carried out on the charcoal data from all study sites, with charcoal counts as the predictor and charcoal area as the response variable. The results of these regressions differ greatly between sites, and highlight the difficulty in predicting total charcoal area of a sample with a single equation (Tinner and Hu, 2003). There are many site-specific process and parameters which may affect the charcoal fragmentation and the relationship between charcoal area and number. A number of outliers were detected within the analysis, and removing them was of little significance to the regression calculations. Charcoal count/area ratios were also calculated for each site and the ratios with the highest values, tended to have the smallest charcoal counts, suggesting that the bias due to particle breakage was negligible. This can be seen in Figure 4.1 overleaf which shows the charcoal area vs. count analysis for Cuckoo and Diheen Lough. In light of these analyses charcoal area measurements have been chosen to generate the fire history interpretations in the subsequent analysis.

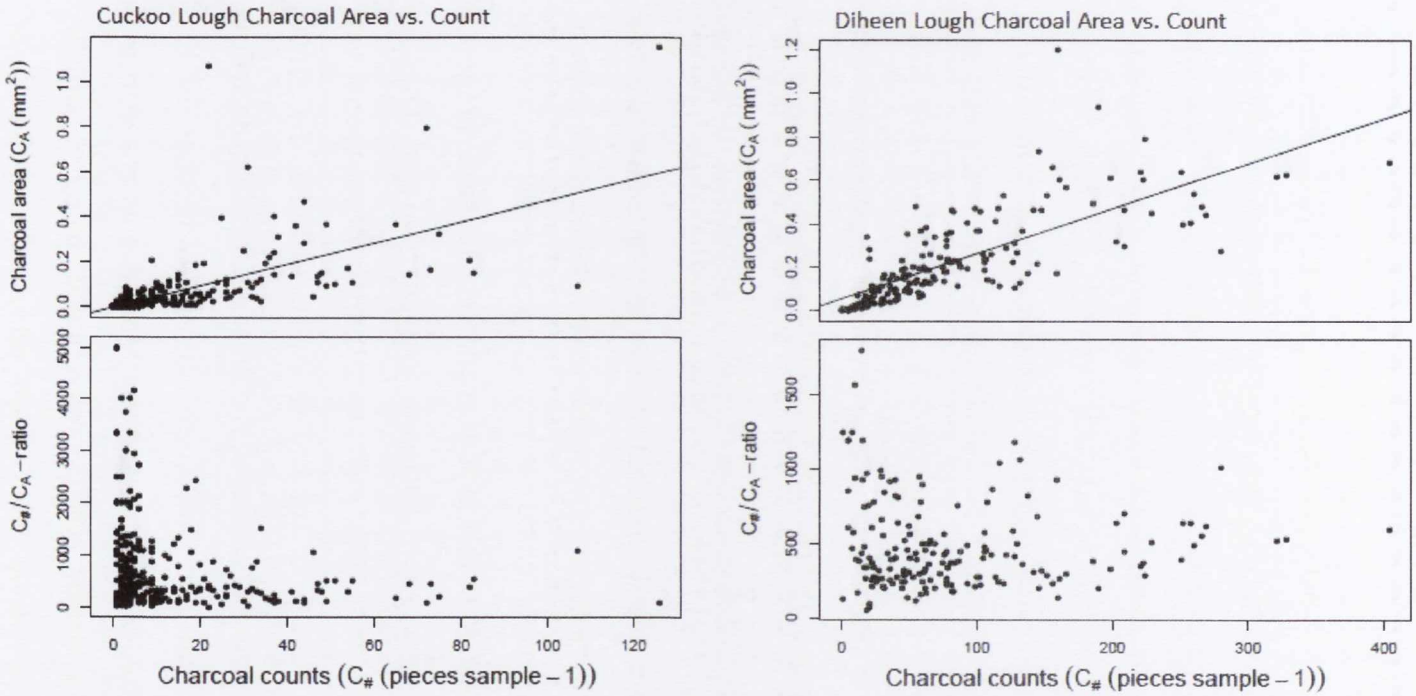


Figure 4.1 Charcoal area and Charcoal count analysis for Cuckoo and Diheen Lough.

4.5.2 Ensemble Member Strategy

As discussed above an Ensemble Member approach was used to assess the different smoothing methods available to separate $Char_{raw}$ into $Char_{noise}$ and $Char_{peak}$, to detect significant fire events. $Char_{raw}$ sequences were used to produce 2350 reconstructions for each study site. Members showing a poorly modelled $Char_{noise}$ sequence i.e. Gof<0.1 were excluded. Within the remaining members the first 1000 showing the highest SNI were selected to produce the final ensemble member. Cuckoo Lough is used here as an example to illustrate the output of the ensemble member analysis. Figure 4.2 shows the SNI and GoF distributions from the Cuckoo Lough analysis. A high SNI is observed with smoothing windows ≥250 years. An optimum smoothing window of 1000 years was selected based on the high SNI and the correspondence with a width of approximately 96 charcoal samples, which is above the 30-sample width recommended for accurate peak detection (Higuera et al., 2009). The GoF data display a general negative correlation with window width, representing periods of low scores where the Gaussian mixture model fails to accurately model the $Char_{noise}$ population. The Moving Mode, LOWESS and Moving Median smoothers are more prone to provide a poor separation between the $Char_{peak}$ and $Char_{noise}$ populations; they have 156, 162 and 194 reconstructions left respectively. The number of robust fire events identified by ≥1000 members was calculated as 32 events, and these are free from analytical bias. Figure 4.3 shows the Fire return interval distributions for the members categorised by filtering method. More events are detected here via the Moving Median, LOWESS and rLOWESS smoothers, with 37 and 36 events respectively. The analysis calculated a mean FRI of between 474 years and 478 years for a Moving Average and LOWESS smoother and 423 years for a Moving Mode smoother. Fire frequency is calculated as the median of the ensemble members. Little divergence can

be seen between the median fire frequency and the fire frequency obtained from a single analysis using an rLOWESS smoother and a 700 year bandwidth. The largest divergence occurs between 8000BP and 5250BP. This shows a good fit between the median of selected members and the parameters described. Taking all these analyses into account a Robust LOWESS smoother and a window width of 1000 years was selected for further analysis on the Cuckoo Lough data. Different fire event reconstructions may be produced based on uncertainties associated with user analytical choices. This analysis aims to produce quality fire event reconstructions from a pool of members based on SNI and GoF criteria. However no ultimate statistical treatment exists and a consensus must be reached based on analyses such as this. Taking this into account the most appropriate smoothing method and window width was selected for each study site to be used in the subsequent CharAnalysis. Table 4.1 includes the smoothing methods and window widths selected for the charcoal analysis, as well as the other user parameters required for the CharAnalysis.

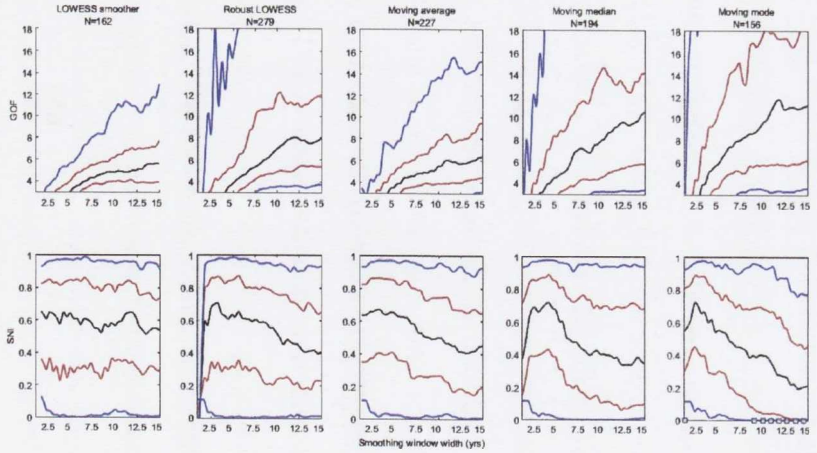


Figure 4.2 Cuckoo Lough Signal to Noise Index (SNI) and Kolmogorov-Smirnov Goodness of Fit (GoF) p-values according to different filtering methods for the Cuckoo Lough charcoal analyses plotted against moving window width (yrs x100). The filtering methods are the following: LOWESS, robust LOWESS, moving average, moving median, and moving mode filters, respectively. The median SNI and GoF are displayed using black lines, the red lines show 25th and 75th percentiles, respectively, and the blue lines show the 5th and 95th percentiles, respectively.

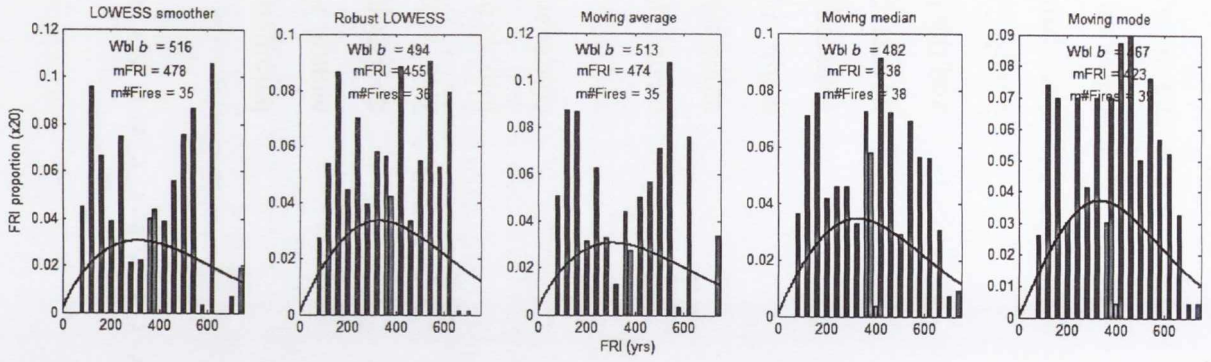


Figure 4.3 Cuckoo Lough FRI distribution following the different filtering methods for Cuckoo Lough charcoal records. FRI distribution associated with each filtering method (grey histogram). Each subfigure provides the fitted Weibull distributions (black line) and the associated Weibull b parameters (Wbl b), the mean number of fire events recorded (m#Fires) and the mean FRI by filtering method (mFRI).

Table 4.1 CharAnalysis Parameters for each study site

Study Sites		Ballinderry	Borheen	Cornaher	Cuckoo	Diheen	Kellys	Sheheree
Stage	Variable							
Pre-Treatment	Zone Division	40-1074.5	-1-12637	3017-11514.5	877.5-17493	-1-858	572.5-11111	617-10499.5
	yr interpolate	0	0	0	0	0	0	0
	Transform	0	0	0	0	0	0	0
Smoothing	Method	4	4	1	2	2	3	3
	Year	600	500	750	1000	300	1000	800
Peak Analysis	C-peak	2	1	2	1	1	2	1
	threshType	2	2	2	2	2	2	2
	threshMethod	3	3	3	3	3	2	3
	threshValues	0.95	0.95	0.9	0.95	0.95	0.99	0.95
		0.99	0.99	0.95	0.99	0.99	0.99	0.99
		1	0.99	0.99	0.99	0.99	1	1
		0.99	0.99	0.95	0.99	0.99	0.99	0.99
	minCountP	0.99	0.99	0.99	0.99	0.99	0.99	0.99
	peakFreq	600	1000	750	14500	300	1000	8000

Zone Division: Years defining beginning and end of record.

yrInterpolate: Years to interpolate record to.

Transform: Transform record before analysis 0 == No; 1 == base-10 log transform; 2 == natural log transform.

Method: Estimate low-frequency CHAR (aka $Char_{back}$) 1 == Lowess smoother; 2 == Lowess smoother, robust to outliers; 3 == moving average; 4 ==moving median; 5 == moving mode.

yr: Years to smooth record over for estimating $Char_{back}$.

cPeak: Calculate high-frequency CHAR (aka $Char_{peak}$)? 1 == residuals ($Char_{peak} = Char_{int} - Char_{back}$); 2 == ratios ($Char_{peak} = Char_{int} / Char_{back}$

threshType: Type of threshold 1 == Globally defined; 2 == Locally defined.

threshMethod: Threshold values for peak identification? 1==user defines threshold values. 2==base values on a percentile: cut-off of a noise distribution., modelled with a 0- or 1- mean Gaussian (for $char_{peak}$ method 1 or 2 respectively). 3==same as 2 but noise distribution is determined by a Gaussian mixture model.

threshValues: Threshold values to evaluate if threshMethod == 1, these values are in $Char_{peak}$ units (i.e. either a residual or ratio value). If threshMethod == 2-3, these values are percentiles of the noise distribution (e.g. 0.95).

minCountP: Cut-off probability for minimum count analysis

peakFreq: Years to smooth fire frequency and fire return interval over.

4.5.3 Fire Events and Magnitude

Using the CharAnalysis software as described within Matlab (Higuera, 2009a), a specific number of fire events and their magnitude were identified at each of the study sites. Figure 4.4 Shows the interpolated charcoal concentration at each of the sites, with each fire event represented by a red cross. Figure 4.4 does not reflect the peak magnitudes discussed below. Peak magnitude is calculated as the sum of all samples exceeding the final threshold for a given peak.

Irish Midlands

Ballinderry Lough

Utilising the charcoal data obtained from Ballinderry Lough, 7 fire events were identified using a Moving Median smoother and an average threshold of 1.33$cm^{2}yr^{-1}$. The events spread fairly evenly throughout the record from 1050BP up until the present day. The two largest peaks in charcoal occur at 103BP and 1021BP with magnitudes of 492.1$cm^{-2}peak^{-1}$ and 172.9$cm^{-2}peak^{-1}$. There is a constant presence of charcoal throughout the 1050 years; however a slight decreasing trend can be seen from the charcoal peak at 913BP until approx. 300BP.

Cornaher Lough

A Lowess smoother was used at Cornaher Lough to identify eight fire events, using an average threshold of 0.77$cm^{-2}yr^{-1}$. Five of the events identified are concentrated between 3000 and 4000BP, with the other three events, notably the three largest peaks in charcoal occurring at 7138BP, 9712BP and 9751BP, with magnitudes of 501.9$cm^{-2}peak^{-1}$, 464.3$cm^{-2}peak^{-1}$ and 25.4$cm^{-2}peak^{-1}$. The record here is dominated by the three large fire events and the cluster of smaller fire events, with the

rest of the record containing very small charcoal peaks or a total absence of charcoal.

Killarney National Park

Cuckoo Lough

Four fire events were identified from the charcoal record at Cuckoo Lough, using a Lowess smoother robust to outliers, with an average threshold value of $0.0008cm^{-2}yr^{-1}$. The four events identified here dominated the record with considerably large peaks in charcoal. Three of the events are located at the bottom of the record between 16000 and 17200BP, while the fourth event occurred earlier at 5172BP. The magnitudes of these peaks are $0.8cm^{-2}peak^{-1}$, $0.004cm^{-2}peak^{-1}$, $0.5cm^{-2}peak^{-1}$, and $1.4cm^{-2}peak^{-1}$ respectively. Between 16000BP and 9500BP there is a low fluctuation in the charcoal record, but from 9000BP to approx. 2000BP there is an increasing trend in charcoal activity, after which the charcoal record disappears towards the present day.

Sheheree Lough

From the final record at Sheheree Lough 3 fire events were identified using a Moving Average smoother and an average threshold of $-0.0029cm^{-2}yr^{-1}$. This record is dominated by one very large peak.This peak occurs at 3879BP with a magnitude of $408.8cm^{-2}peak^{-1}$, representing a major fire event. Two smaller fire events occur at 9752BP and 9962BP, with magnitudes of $1.78cm^{-2}peak^{-1}$ and $1.05cm^{-2}peak^{-1}$ respectively. The dominance of the very large peaks makes it difficult to observe the smaller charcoal trends and peaks occurring throughout the record.

Galty Mountains

Borheen Lough

Five fire events were identified from the charcoal record at Borheen Lough, using a Moving Median smoother and an average threshold of 0.0081$cm^{-2}yr^{-1}$. All the events in this record are concentrated between 2000BP and the present day, the rest of the record from 2000-12000BP has miniscule charcoal peaks or no presence of charcoal at all. The largest peak in charcoal can be seen clearly here and occurs at 1231BP with a magnitude of 72$cm^{-2}peak^{-1}$, with the second two largest peaks being located on either side of this, at 607BP and 1519BP, with magnitudes of 4.9$cm^{-2}peak^{-1}$ and 0.71$cm^{-2}peak^{-1}$.

Diheen Lough

Examining the charcoal record at Diheen Lough, 10 fire events were identified using a Lowess smoother robust to outliers, with an average threshold of 0.032$cm^{-2}yr^{-1}$. The events identified here are spread very evenly throughout the record, occurring from approx. 750BP to 150BP. There is a constant presence of charcoal throughout this record with a similar trend in variability throughout. There is a high frequency of large peaks, but the two largest peaks occur at 395BP and 159BP with magnitudes of 5.15$cm^{-2}peak^{-1}$ and 3.4$cm^{-2}peak^{-1}$.

Wicklow Mountains

Kelly's Lough

Using a moving average smoother and an average threshold of 2.48$cm^{-2}yr^{-1}$, 5 fire events were identified at Kelly's Lough. These events are

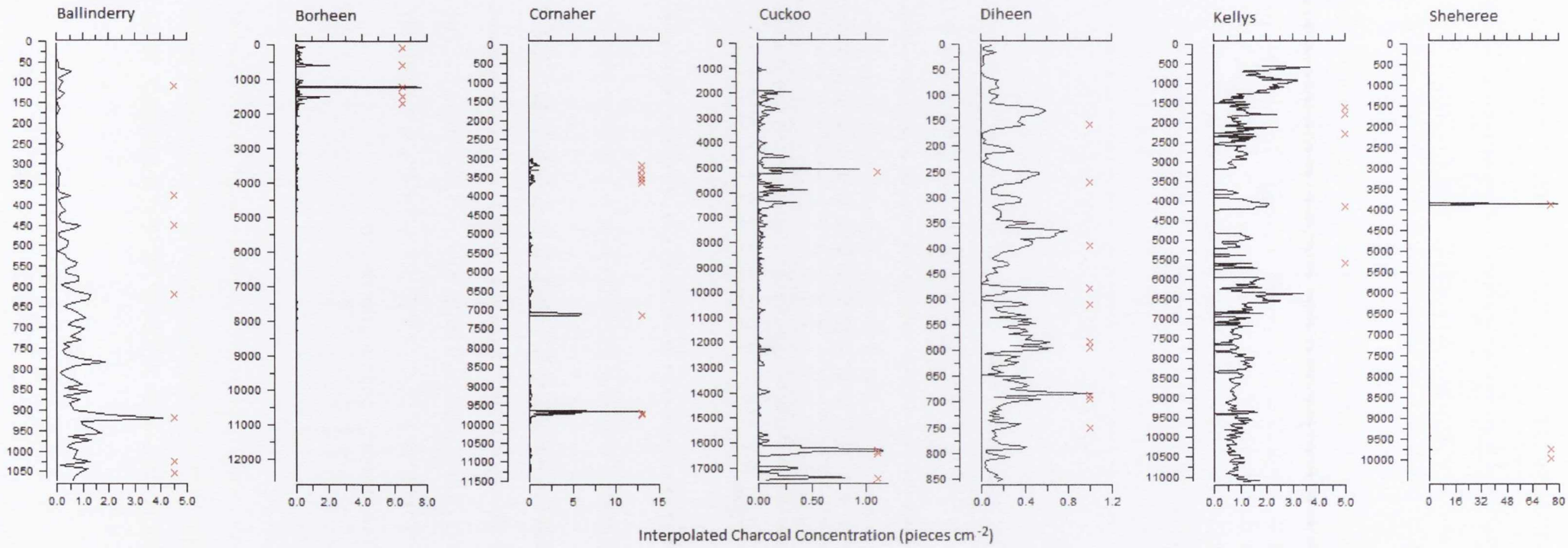


Figure 4.4 Interpolated charcoal concentration (pieces.cm^{-2}) plotted against age (BP) with identified fire events represented as red crosses.

concentrated in the top half of the record from approx. 6000BP to 1000BP, there is a constant presence of charcoal throughout the record, with an increased frequency towards the present day. The largest charcoal peak occurs at 4137BP with a magnitude of 75.7$cm^{-2}peak^{-1}$, the four other peaks range in magnitude from 1.36$cm^{-2}peak^{-1}$ at 1617BP to 9.27$cm^{-2}peak^{-1}$ at 1779BP.

4.5.4 Fire Frequency

The fire frequency reported here was calculated using a Gaussian kernel, with inputs of fire event years and bandwidth, using maximum log likelihood (Blarquez et al., 2013). Fire frequency is a mathematical expression of fire occurrence and shows the general trend of how fire events increase and decrease over time. Figure 4.5 Displays the fire frequency calculated for each of the study sites with the fire events depicted as red crosses.

Irish Midlands

Ballinderry Lough

The fire frequency here is relatively constant throughout the record; however it does display a slight decreasing trend towards the present day. It decreases from approx. 0.009$fire.yr^{-1}$ to 0.005$fire.yr^{-1}$. The somewhat steady frequency here reflects the constant and relatively equal spread of fire events throughout the record.

Cornaher Lough

The fire frequency record displayed at Cornaher Lough shows a varied frequency ranging from 0 to approx. 0.002$fire.yr^{-1}$, with slight peaks associated with three fire events at 7138BP, 9712BP and 9751BP. There

is a large peak in fire frequency at approx. 3500BP where there is a concentration of five fire events with a peak frequency of approx. 0.002fire.yr^{-1}. After which the fire frequency decreases again to 0 towards the present day.

Killarney National Park

Cuckoo Lough

One of the most linear fire frequencies occurs here at Cuckoo Lough, it displays a decreasing trend from a frequency of 0.0004fire.yr^{-1} to a frequency of 0.0001fire.yr^{-1} at the present day. There are four fire events identified at this site and three occur at the bottom of the record where the fire frequency is slightly higher, between 16000 and 17000BP, while the third occurs at approx. 5000BP where the fire frequency has decreased slightly.

Sheheree Lough

The fire frequency at Sheheree Lough shows a general decreasing trend from 0.0005fire.yr^{-1} at 10500BP to 0.0001fire.yr^{-1} at the present day. Three fire events were identified at Sheheree Lough, two of which are fairly close together at the bottom of the record corresponding to the higher fire frequency here, while the third is located at approx. 4000BP where there is a lower fire frequency, which continues to decrease towards the top of the record.

Galty Mountains

Borheen Lough

At Borheen Lough the fire frequency remains at 0 until approx. 3000BP when it rises sharply to approx. 0.002fire.yr^{-1}, where it remains until the record reaches the present day. This pattern of fire frequency reflects the

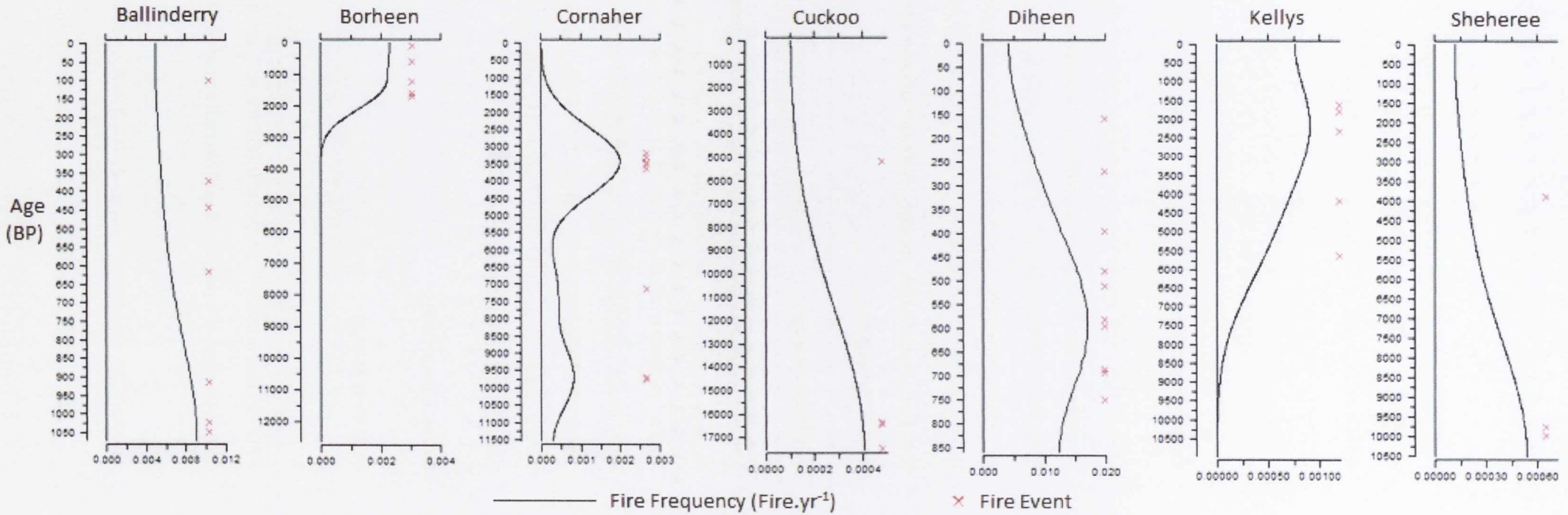


Figure 4.5 Fire frequency (fire.yr^{-1}) plotted against age (BP) with fire events identified as red crosses.

distribution of the fire events which are concentrated between 0 and 2000BP.

Diheen Lough

The fire frequency record at Diheen Lough also displays a decreasing linear trend, decreasing from a fire frequency of approx. 0.017fire.yr^{-1} at 600BP to 0.004fire.yr^{-1} towards the present day. The ten fire events identified at this site cover the majority of the record, with a slightly higher concentration at approx. 600BP where the fire frequency peaks.

Wicklow Mountains

Kelly's Lough

Five fire events were identified from the record at Kelly's Lough and the fire events are concentrated in the top half of the record from approx. 6000BP to 1000BP. The fire frequency increases from 9000BP and peaks at 0.0009fire.yr^{-1} at approx. 2000BP, reflecting the concentration of three fire events near the top of the record. The fire frequency continues to remain high but dips slightly towards the present day.

4.5.5 Fire Return Interval

Fire return intervals were calculated for each fire event identified at each of the study sites, the intervals represent the number of years between each event. Figure 4.6 Shows the calculated fire return intervals at each site, as well as a mean smoothed over a specified time window using a Lowess smoother (Higuera, 2009a). Fire return intervals can be used to potentially predict when a future fire is likely to occur.

Irish Midlands

Ballinderry Lough

Six fire return intervals were calculated at Ballinderry Lough corresponding to the identified fire events. There is a wide range of fire return intervals present at this site, from 27yr.fire^{-1} to 297yr.fire^{-1}. The largest fire return interval occurring at approx. 600BP. The smallest fire return intervals occur at 1025BP and 375BP where there are a number of fire events quite close together and have return intervals below 80yr.fire^{-1}. The mean fire return interval here was calculated as 157.5yr.fire^{-1} with confidence intervals of 87yr.fire^{-1} and 238yr.fire^{-1}. An alternative calculation of the maximum likelihood estimate of the Weibull b parameter over a window of 600 years produced a fire return interval calculation of 173 years. The 95% confidence interval associated with this calculated from 1000 bootstrapped samples was between 88 and 260 years.

Cornaher Lough

Seven fire return intervals were calculated at Cornaher Lough, they increase in length until approx. 3500BP from an interval of 104yr.fire^{-1} to 3484yr.fire^{-1}. Four fire events are located between 3000BP and 4000BP with smaller fire return intervals. The mean fire return interval calculated here is 936yr.fire^{-1} with confidence interval bounds of 89yr.fire^{-1} and 2037yr.fire^{-1}. The Weibull maximum likelihood estimate for the b parameter was calculated for the fire return intervals within a 750 year smoothing zone, and produced a value of 324.5 years. A 95% confidence interval was also calculated in conjunction with this, based on 1000 bootstrapped samples and produced an interval between 97 and 679 years.

Killarney National Park

Cuckoo Lough

At Cuckoo Lough three fire return intervals were calculated for the four fire events identified. The smaller two fire return intervals occur between 16,000BP and 16500BP with intervals of 76yr.fire^{-1} and 1076 yr.fire^{-1}, while the third fire return interval occurs at approx. 5100BP with a value of 11,172yr.fire^{-1}. The mean fire return interval and maximum likelihood estimate of the Weibull b parameter were not calculated in this case due to the low number of fire return intervals within each smoothing zone. The goodness of fit of the Weibull model tested using a Kolmogorov-Smirnov test was also invalid in this case.

Sheheree Lough

The charcoal analysis at Sheheree Lough identified three fire events, with the record being dominated by one very large peak at approx. 3800BP. Two fire return intervals were calculated at this site and range from the smallest interval of 210yr.fire^{-1} to the largest interval of 5873yr.fire^{-1}. Like at Cuckoo Lough the mean fire return interval and maximum likelihood estimate of the Weibull b parameter were not calculated at this site due to the low number of fire return intervals within each smoothing zone. The goodness of fit of the Weibull model tested using a Kolmogorov-Smirnov test was also invalid in this case.

Galty Mountains

Borheen Lough

The fire events identified at Borheen Lough are all concentrated between 0 and 2000BP. The fire return intervals range from the shortest interval at 192yr.fire^{-1} to the largest at 624yr.fire^{-1}. The general trend in fire

return intervals is increasing towards the present day, with a slight reduction in fire return interval for the last fire event identified. The mean fire return interval was calculated as 404yr.fire^{-1}, with upper and lower confidence intervals of 240yr.fire^{-1} and 568yr.fire^{-1}. The maximum likelihood of the Weibull b parameter with respect to the fire return intervals in a 1000 year window was calculated as 458 years. And a bootstrapped 95% confidence interval over 1000 samples was calculated as between 257 and 593 years.

Diheen Lough

Diheen Lough displays the least variance in fire return intervals, with all six intervals occurring between 9yr.fire^{-1} and 124yr.fire^{-1}. The smoothed fire return interval displays an increasing trend from 825BP towards the present day. The mean fire return interval calculated here is 65.8yr.fire^{-1} with upper and lower confidence intervals of 40yr.fire^{-1} and 90yr.fire^{-1}. The Weibull b parameter used to calculate the maximum likelihood estimate produced a fire return interval value of 80 years. The calculated 95% confidence interval using 1000 bootstrapped samples is between 52 and 103 years.

Wicklow Mountains

Kelly's Lough

Five fire events were identified at Kelly's Lough, and the fire return intervals reflect the clusters of fire events identified between 6000BP and 1000BP. The fire return intervals increase from 1500BP to 2000BP from an interval of 162 years to 1836 years. The final fire return interval occurs at 4137BP with a value of 1458yr.fire^{-1}, and is slightly lower than the previous fire return interval. The mean fire return interval was calculated as 995yr.fire^{-1}, with a confidence interval of 342yr.fire^{-1} to 1647yr.fire^{-1}. The calculated Weibull likelihood estimate of the b parameter was calculated at 753 years, with a 95% confidence interval

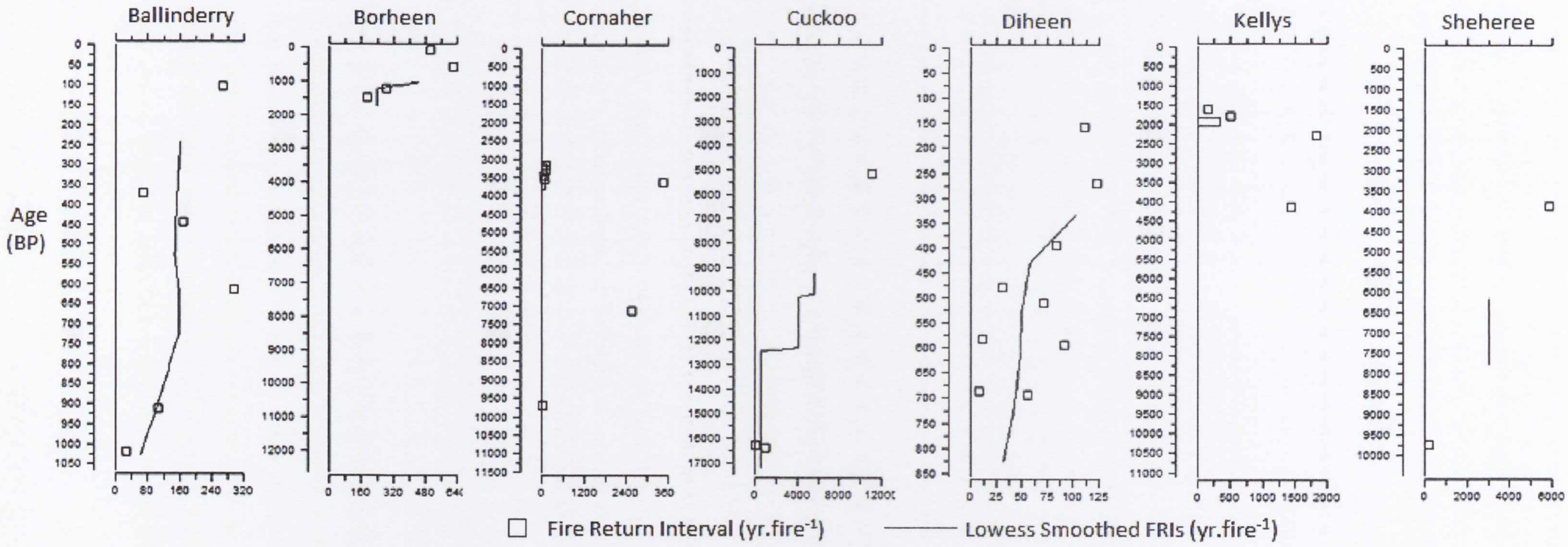


Figure 4.6 Fire return intervals (yr.fire^{-1}) plotted against age (BP)

estimated between 386 and 1000 years.

Model Validation

The results presented above are based on valid statistical tests but in order to present these results with added confidence, a number of further tests have been carried out to specifically test the validity of the records presented. The first is a signal to noise index and the second is a charcoal peak screening method, the results of which are reported below.

4.5.6 Signal to Noise Index

A signal to noise index tests whether a charcoal record is appropriate for peak detection i.e. is there adequate separation between the background and peak charcoal within a record. Figure 4.7 shows the signal to noise index calculated at each study site via both the CharAnalysis method proposed by Higuera (2009a), and the new method discussed previously by Kelly et al. (2011). The window width for computing and smoothing the signal to noise index was chosen specifically for each site and it matches the window width chosen to compute background charcoal.

Irish Midlands

Ballinderry Lough

The signal to noise index calculated at Ballinderry Lough using the method described by Kelly et al. (2011) produced a value of 0 throughout the record. This occurs when none of the signal samples exceed the specified threshold. The rest of the calculations associated with this also therefore produced a value of 0. The signal to noise index calculated using the method described by Higuera (2009a), produced an average

SNI of 9.1, well above the accepted threshold of 3 which identifies records appropriate for peak detection.

Cornaher Lough

The signal to noise index calculated at Cornaher Lough via Kelly's method produced an average value of 1.96; this lower value is due to the large number of zeros within the record, caused by samples which failed to exceed the specified threshold. The signal to noise index values range from 0-25.6 with 13.6% of the values greater than the critical value of 3 determining whether the record is appropriate for peak detection. The average signal to noise index calculated using Higuera's method is 12.7, and has values ranging from 4-147.9.

Killarney National Park

Cuckoo Lough

The two signal to noise distributions calculated at Cuckoo Lough produced a similar trend in values, which can be seen in Figure 4.7. The average signal to noise index calculated using Kelly's method is 12.51 with values ranging from 0-57.2, and 89.7% of the record includes values above the critical value of 3. In contrast using Higuera's method the average signal to noise index produced a value of 10.1, with values ranging from 3.1-40.1.

Sheheree Lough

Kelly's and Higuera's method of signal to noise calculations produced very similar trends at Sheheree Lough. They produced average values of 25.72 and 16.5 with indexes ranging from -0.13-130.94 and 0-130.6 respectively. 91% of values produced via Kelly's method and 82% of values produced by Higuera's method exceed the recommended

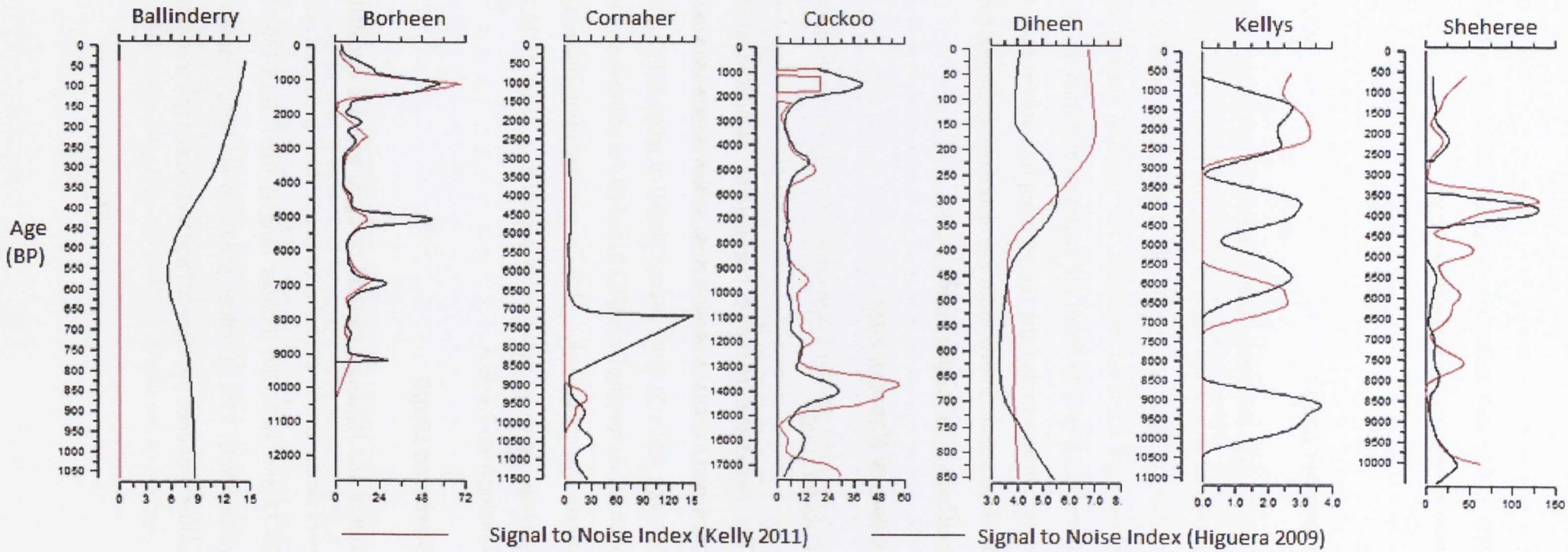


Figure 4.7 Signal to noise index calculated using two different methods plotted against age (BP).

threshold of 3, signifying that the record is appropriate for peak detection. The two distribution show similar trends and can be seen in Figure 4.7.

Galty Mountains

Borheen Lough

At Borheen Lough the signal to noise trend calculated using the method outlined by Kelly, had values ranging from 0 to 69.4, and an average signal to noise index of 8.54, which again is above the critical value of 3. Looking at the entire record 63.6% of values were above this critical value. Comparing this analysis with the signal to noise index calculated using the Higuera method, it produced a slightly higher average signal to noise index of 9.8. Looking at both signal to noise distributions for Borheen Lough, shown in figure 4.7 it can be seen that the two distributions follow a similar trend throughout the record.

Diheen Lough

Using Kelly's method of calculation an average value of 4.9 was produced for the signal to noise distribution. The values range from 3.6-7.03 with 99.5% of the distribution above the critical value signifying appropriate separation between the signal and noise population. Using Higuera's method a slightly lower signal to noise distribution was produced with an average value of 4.2 and values ranging from 3.3-5.6. The two signal to noise trends can be seen in Figure 4.7.

Wicklow Mountains

Kelly's Lough

The signal to noise distribution from Kelly's Lough displays some similar patterns and contains peaks with a comparable magnitude. Average

signal to noise indexes of 0.85 and 1.43 were produced for Kelly's and Higuera's method respectively. Kelly's signal to noise index had a range between 0 and 3.3, while Higuera's method had a signal to noise index ranging from 0 to 3.7. Kelly's Lough has one of the lowest signal to noise index distributions, with only 7.9% of values greater than the critical value of 3 using Kelly's method. Using Higuera's method and the recommended threshold of 0.5, 67% of values are above this critical value.

Table 4.2 Signal to noise index results calculated using Kelly's and Higuera's (italicized) method.

Study Site	Ballinderry	Borheen	Cornaher	Cuckoo	Diheen	Kellys	Sheheree
Mean SNI	0 *9.1*	8.54 *9.8*	1.96 *12.7*	12.51 *10.1*	4.9 *4.2*	0.85 *1.43*	25.72 *16.5*
Median SNI	0 *8.4*	6.34 *6.98*	0 *6.9*	9.39 *6.8*	3.97 *3.99*	0 *1.45*	18.93 *9.6*
Min-Max SNI	0 *5.57-14.5*	0-69.4 *0-57.7*	0-25.6 *4-147.9*	0-57.2 *3.1-40.1*	3.6-7.03 *3.3-5.6*	0-3.3 *0-3.7*	-0.13-130.94 *0-130.6*
% SNI>3	0 *100*	63.6 *73*	13.6 *100*	89.7 *100*	99.5 *100*	7.9 *7.7*	91 *82.4*
%SNI>0.5	0 *100*	66.6 *73*	15.6 *100*	89.7 *100*	99.5 *100*	35.3 *67*	97.7 *84*

4.5.7 Charcoal Peak Screening

The second method of validation used in this study tests whether each identified peak is likely to occur due to something other than chance i.e. charcoal peaks are screened to guard against interpreting potential insignificant peaks as fire episodes (Finsinger et al., 2014a). The analysis compares reconstructions based on charcoal area and charcoal count, and flags peaks with a total area greater than the likely range expected

by chance ($p<0.05$), as robust indicators of fire events. Figure 4.8 and 4.9 show the screened charcoal peaks for $Char_{area}$ for each of the study sites.

Irish Midlands

Ballinderry Lough

The charcoal area reconstruction at Ballinderry Lough identified seven fire events however none of these peaks passed the charcoal peak screening analysis. The peaks are below the bootstrapped threshold and therefore cannot be characterised as significant fire events. Looking at the reconstruction for the charcoal count data nine fire events were identified, with five peaks passing the screening test and four peaks lying below the critical bootstrapped threshold. The significant and non-significant peaks identified by both the charcoal area and count data follow a similar distribution, supporting the strong positive correlation between count and area data at Ballinderry Lough.

Cornaher Lough

The charcoal peak screening here identified three out of the eight fire events flagged via the CharAnalysis programme, as robust fire events ($p<0.05$). These three peaks, at 3199BP, 3472BP and 3550BP had a charcoal area that exceeded the bootstrapped threshold value, while the remaining five peaks had a charcoal area that fell below this threshold, suggesting that their occurrence is due to chance variation. Looking at the charcoal count reconstruction there was again a considerably larger number of fire events identified i.e. fifty eight. Forty eight of these events are characterised as robust fire events, while ten did not pass the charcoal peak screening method and are classed as insignificant charcoal peaks. The two reconstructions differ significantly however taking signal to noise index and charcoal count vs. area ratio into account, charcoal area is still an appropriate tool for fire event reconstruction.

Killarney National Park

Cuckoo Lough

For the charcoal area reconstruction at Cuckoo Lough, all four of the fire events identified via the CharAnalysis programme passed the charcoal peak screening. All four charcoal peak areas were above the bootstrapped thresholds and are characterised as robust fire events ($p<0.05$). These events occur at 5172BP, 16344BP, 16420BP and 17446BP. Like the previous sites analysed the charcoal count reconstruction here also produces more fire events i.e. thirty, with twenty three passing the charcoal peak screening, and seven residing below the critical thresholds and classed as insignificant charcoal peaks. The variation in the two reconstructions again produces differing fire return intervals and fire frequencies.

Sheheree Lough

All three fire events identified from the charcoal area data at Sheheree Lough, passed the charcoal peak screening analysis. All three peaks were above the critical threshold identified via the bootstrapping method, and are therefore identified as robust fire events ($p<0.05$). Like the previous study sites, a larger number of fire events are identified using the charcoal count data. At Sheheree Lough fifty four events were identified, with thirty two passing the charcoal peak screening analysis and twenty two failing to pass the screening. The identified events from both the charcoal area and count data are clustered around two main concentrations of charcoal peaks at approx. 4000BP and 9500BP.

Galty Mountains

Borheen Lough

At Borheen Lough, for the reconstruction based on charcoal area, four out of the five fire events identified via the CharAnalysis programme passed the charcoal peak screening method. These events at 95BP, 607BP, 1231BP and 1711BP have been identified as robust fire events ($p<0.05$), with a char value exceeding the bootstrapped threshold. The final peak at 1519BP failed to pass the peak screening test as the char value was below the calculated threshold, suggesting that the presence of this peak is due to chance variation within the record. Comparing these events identified with the charcoal count data, there is a significantly larger number of fire events identified via the count data. Forty-Nine fire events were identified with forty two passing the charcoal peak screening test, considering them robust fire events, and seven failing to exceed the calculated threshold, deeming them insignificant charcoal peaks. This is a considerable variation which would result in differing fire return intervals and fire frequency.

Diheen Lough

At Diheen Lough six out of the ten fire events identified via the CharAnalysis programme passed the charcoal peak screening. These six events are now characterised as robust fire events ($p<0.0.5$) and all exceeded the bootstrapped threshold. The four remaining events that did not pass the charcoal peak screening fell below the critical threshold. The robust fire events occurred at 159BP, 395BP, 479BP, 687BP, 695BP and 751BP. Looking at the count charcoal reconstruction, eighteen fire events were identified and all eighteen events passed the charcoal peak screening. The six robust events identified via the charcoal area data correspond to similar robust events reflected by the charcoal count data.

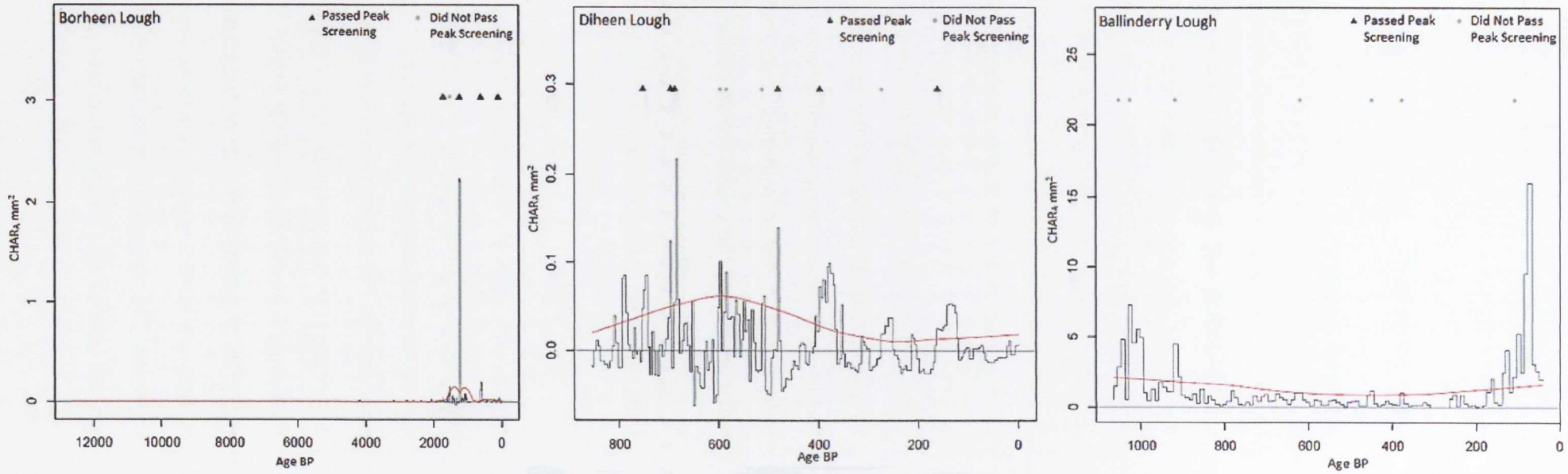


Figure 4.8 Multisite Charcoal Peak Screening ($Char_{area}$) for Borheen, Diheen and Ballinderry Lough (red line represents threshold used, specific to each site).

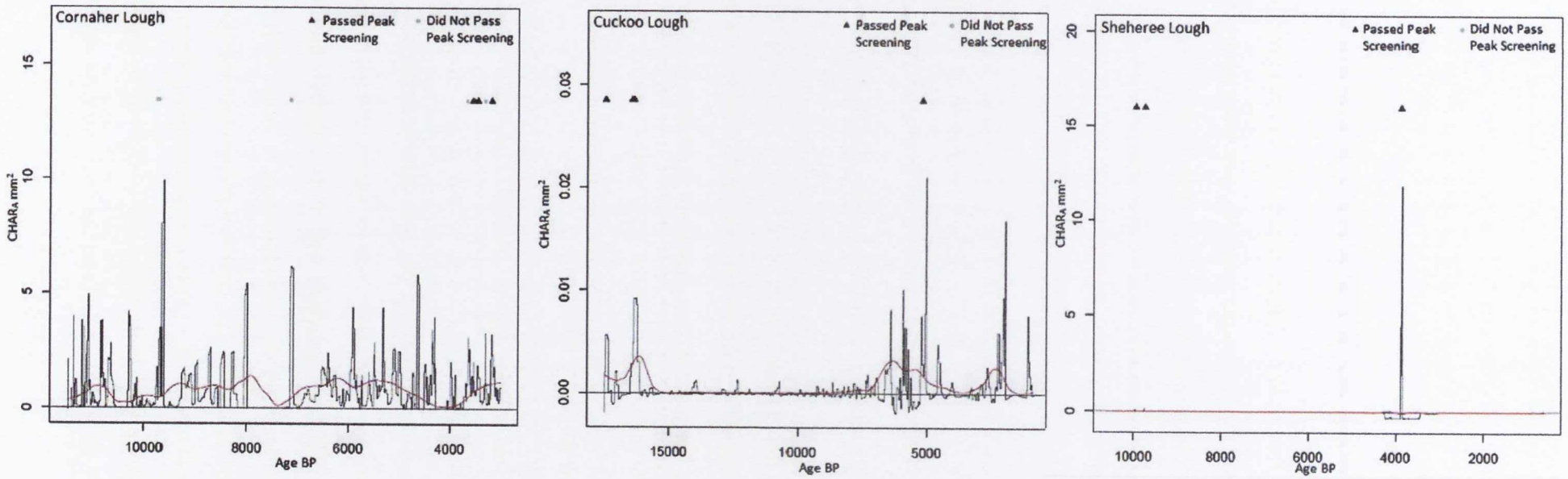


Figure 4.9 Multisite Charcoal Peak Screening ($Char_{area}$) for Cornaher, Cuckoo and Sheheree Lough (red line represents threshold used, specific to each site)

Wicklow Mountains

Kelly's Lough

The charcoal data from Kelly's Lough could not be included in the charcoal peak screening analysis because the data were generated as part of a previous project, using Scion Image analysis rather than Image J, and therefore individual charcoal particle areas were not available, and this is a required input for the analysis.

4.6 Discussion

The results presented in this chapter are the culmination of a variety of methods selected to analyse and reconstruct an accurate record of past fire regimes at 7 sites spread throughout Ireland. These methods were selected based on a number of criteria; the most recent and widely accepted methods, the methods most suited to the nature of the data collected, and the methods most appropriate and useful for the aim of reconstructing past fire history. I now present a critical review of the methods used within this chapter and the justification for their use.

Field Work and Laboratory Methods

As is standard in palaeolimnological studies a sediment core was obtained via a coring process at each of the seven study sites. A Livingstone corer was used to extract the sediment from the bottom of the lake and has been widely used since its introduction (Livingstone, 1955, Smol et al., 2002). It provides the most effective method of sediment extraction ensuring the complete core is intact with limited contamination of the sediment. The charcoal preparation method used for the macrocharcoal follows that of Mooney and Radford (2001), which is a slightly modified approach to that previously described by Millspaugh and Whitlock (1995), Long et al. (1998) and Gardner and Whitlock (2001).

All methods involve a volume of sediment being treated with sodium hexametaphosphate and bleach to produce a petri dish of charcoal. These methods were used as they provide a quick, easy and effective process of charcoal extraction, enabling batches of up to 60 samples to be processed at any one time. A $1cm^3$ sample was used in the analysis, and this has been proven to be the minimal volume required to produce replicable results (Carcaillet, 2001), and there is little difference between the reconstructions when a larger volume of sediment is used. A sieve of 125 microns was also selected for use in the laboratory analysis to distinguish the macro charcoal, and this has been seen to represent a localised charcoal input into the lake i.e. <7km from the fire (Whitlock and Millspaugh, 1996, Gardner and Whitlock, 2001). The macro-charcoal fragments can also be counted under the microscope or via a digital image analysis, and in recent years there has been an increase in the digital method of counting (Thevenon and Anselmetti, 2007, Mooney, 2011, Crawford and Belcher, 2014). It provides a simple, fast method which produces accurate count and area estimates for each sample (Stevenson and Haberle, 2005). It has been stated previously that image analysis estimates are often lower than those determined by eye (MacDonald, 1991, Horn, 1992), because particle edges have a lower optical density than the centre, resulting in small particles not being observed and larger particles appearing smaller. Image J an image analysis program has become widely used and has been proven more accurate, where it is possible to set a specific threshold to identify the charcoal particles, and it has largely replaced a previously used program Scion Image (Abràmoff, 2004). A comparitive analysis was outlined in Chapter 2, which compared the digital and microscope count of 10 charcoal samples, which reiterates that both methods are comparable. In light of this, the macro-charcoal record and digital image analysis was used for the fire reconstructions presented in this chapter. An adequate chronology is necessary in any high resolution palaeolimnological study. The sediment cores used in this analysis were non-varved and thus were

dated using AMS ^{14}C dating of macrofossils and bulk sediment. Bchron, a statistical package in R, was selected to calibrate the dates and produce a reliable chronology (Parnell et al., 2008). This package was selected as it has been widely used in many previous studies and found to be reliable, it is relatively easy to use and uses the most up to date calibration curve i.e. Intcal13. The laboratory and dating methods described here were found to be effective in this study, as well as other studies in the US (Krause and Whitlock, 2013, Whitlock and Bartlein, 2004, Higuera, 2009b), Europe (Robin and Nelle, 2014, Burjachs and Expósito, 2014, Cui et al., 2015) and Australia (Black et al., 2008, Mooney, 2011, Lynch et al., 2007) using similar procedures, and they form the basis for the data analysis to follow.

Charcoal Area vs Charcoal Count

A correlation analysis was carried out at each of the study sites using a Spearman's Rank Correlation Coefficient. This method allows a quick and easy identification of the relationship between charcoal area and charcoal count. It has been used previously to examine charcoal data (Murphy, 2008) and its use extends to a wide variety of other disciplines. A Spearman's Correlation was chosen because it represents a non-parametric test, and it does not make any prior assumptions about the data (Hauke and Kossowski, 2011) which is more appropriate when considering charcoal data. A number of studies indicate that charcoal count and charcoal area are significantly correlated (Tinner and Hu.,2003; Carcaillet 2007), therefore providing comparable fire history interpretations. The Spearman's correlation carried out on the sites in this study, showed a unified significant positive correlation between area and count, suggesting that both metrics will provide a valid fire history reconstruction. The Rho values ranged from 0.64 at Cuckoo Lough to 0.98 at Cornaher Lough, all with a p-value of less than 0.0001 significance. Ali et al., (2009) carried out a similar analysis which also supports this conclusion showing a positive correlation between charcoal count and

area between two sites in western Quebec, Canada. In light of these analyses charcoal area was chosen to generate the fire regimes in this chapter, and is commonly used in a range of studies from Europe (Marcisz et al., 2015), America (Pilkington and Walsh, 2015) and Australia (Williams et al., 2015). This analysis therefore provides a quick and easy method to test the relationship between the two charcoal measures, informing the decision of which metric to use in the fire history reconstruction. A regression analysis was then carried out between charcoal count and charcoal area for all of the study sites using a method similar to Finsinger et al. (2014a). The regression tested the relationship between charcoal counts and area; however there was a significant difference in the results between sites, with many sites also containing a number of outliers. This suggests that the relationship between the two variables is not direct, and highlights the difficulty in predicting charcoal area with a single equation. This method therefore added little to the analysis, only to emphasise that the relationship between charcoal count and area is more complex. Finally a set of comparison plots were used to compare the charcoal count/area ratios against the charcoal counts, for each of the study sites. This method can be compared to similar analyses carried out by Leys et al. (2013) and Finsinger et al. (2014a), to test the possible effect of particle breakage. The plots for Borheen, Cornaher, Cuckoo and Sheheree Lough display the trend of high charcoal count/area ratios and low charcoal counts, representing negligible particle breakage. The remaining sites Ballinderry, Diheen and Kelly's Lough display a more scattered plot indicating the possibility of more particle breakage at these sites. This method provides a possible indicator of particle breakage, but the results indicate that the relationship cannot solely be determined using this method. Alternative distributions such as those at Ballinderry, Diheen and Kelly's Lough may be produced due to a variation in fire severity or the distance to a burnt area, which can influence the magnitude of charcoal peaks and the likelihood of finding large charcoal particles (Finsinger et al., 2014b,

Conedera et al., 2009). The analysis here highlights the difficulty in determining particle breakage from the charcoal record, and additional factors other than charcoal area and count need to be considered.

Ensemble Member Strategy

The introduction of the Ensemble Member strategy has been a significant development in the charcoal analysis process. It removes some of the objectivity associated with the user defined interface associated with the CharAnalysis program, and aims to select a quality fire history reconstruction from a pool of members based on statistical accuracy and rational criteria i.e. signal to noise index and goodness of fit (Blarquez et al., 2013). Based on these criteria this analysis allows the accurate selection of an appropriate $Char_{raw}$ filtering method and smoothing window width, which can affect the nature of the fire history reconstruction. The analysis worked well for the majority of charcoal records, however the two sites from the Galty Mountains, Borheen and Diheen Lough did not produce accurate results. Blarquez et al., (2013) does caution that this analysis should only be carried out on robust charcoal records. Inaccurate results may be produced if charcoal peaks are small, where the sedimentation rate is slow and peaks are difficult to distinguish from background trends. Much of the charcoal concentration at Borheen Lough tends to be significantly less than 1 piece cm^{-3}, with a few peaks at the top of the record as large as 8 pieces cm^{-3}. The record at Diheen Lough is similar in that the charcoal concentration remains low, below 1 piece cm^{-3} for the entire record, however there are more frequent peaks and declines in charcoal. These low levels of charcoal may have influenced the inaccuracy of the ensemble member analysis here. As this method is a new addition to charcoal analysis, there is a significant lack of comparable literature. The method identified an appropriate smoothing method and window width for the remaining study sites. A Moving Average smoother was identified for Kelly's and Sheheree Lough, with a Lowess smoother and a Lowess smoother robust to outliers was

identified for Cornaher and Cuckoo Lough respectively. Finally a Moving Median smoother was identified for Ballinderry Lough. The window widths identified via the ensemble analysis also vary considerably with study sites, they range from a width of 600 years at Ballinderry Lough to 1000 years at Cuckoo Lough. This analyses highlights the uniqueness of the charcoal record represented at each site, and the sensitivity of the data to the two parameters. The type of smoothing method and window width identified depends on the nature of the charcoal data from each site; the charcoal concentration, number of peaks and the magnitude of peaks identified. This method is useful in the charcoal analysis process as it allows an accurate statistical method to back up some of the user defined choices necessary for the fire history reconstruction via the CharAnalysis program (Higuera, 2009b). Due to the infancy of the ensemble member analysis caution is needed when applying the parameters to the CharAnalysis programme and the parameters should be chosen in consideration of the data from each study site. This method was carried out within Matlab and a certain proficiency in using this software is required. A script is provided by the author (Blarquez et al., 2013) however a number of modifications were necessary for the program to run effectively with the data presented in this chapter.

CharAnalysis

Since its creation CharAnalysis (Higuera, 2009b) has been widely used as an accepted program for fire history reconstruction, providing a platform for reconstruction in a variety of locations around the globe (Morris et al., 2014, Anderson and Stillick, 2013, Bakker et al., 2013, Olsson et al., 2010). New statistical and theoretical knowledge regarding charcoal analysis has allowed its development, building on previous programs such as CHAPS (Bartlein, unpublished software), Charster (Gavin et al., 2006) and CharSim (Higuera et al., 2006). The analysis is based on the widely applied approach that decomposes a charcoal record into a high and low frequency components (e.g. (Clark and Royall, 1996, Long et al.,

1998, Carcaillet, 2001, Gavin et al., 2006). The CharAnalysis program was used to produce fire history reconstruction at all 7 of the study sites used in this analysis. The parameters selected via the previous ensemble analysis were used in the reconstructions for Ballinderry, Cornaher, Cuckoo, Kelly's and Sheheree Lough, and produced accurate results. The remaining parameters were selected based on the best fit for the charcoal distributions represented. After setting up the program and negotiating the user defined input, it is relatively easy to run the program within Matlab. The difficulty comes in the deeper understanding of the statistical analysis that is being carried out and deciding which input parameters are appropriate for the nature of each set of data. Small changes in the input parameters can significantly affect the fire history reconstruction and these should be chosen with care (Higuera et al., 2011). The decision was made not to transform the charcoal record at any of the study sites prior to peak detection. This is because the goal of this study is peak detection, and transformation of the charcoal record can lead to the exaggeration of some peaks and suppression of others. Each of the charcoal records were interpolated to a median sample resolution to account for unequal sampling intervals resulting from variable sediment accumulation rates. The interpolation also removes potential bias to a particular portion of the record, and standardises within and between site comparisons. The median sample resolutions were similar at Diheen, Sheheree and Ballinderry Lough with 4, 7 and 9 years respectively. Also at Borheen, Cornaher and Kelly's Lough where the median resolution was 16, 13 and 19 years respectively. The largest sample resolution was observed at Cuckoo Lough, with 38 years; this record is also the longest in the study spanning from the present day back 18,000 years. For each of the records the thresholds were locally defined, and the threshold values were based on a percentile of a noise distribution, modelled with a 0- or 1-mean Gaussian, with the noise distribution determined by a Gaussian mixture model. This method removes the subjectivity associated with choosing a threshold value for

peak detection. The background trend has been removed from the charcoal records by either subtraction or division, creating a series of residuals or indices respectively. At three sites, Ballinderry, Cornaher and Kelly's Lough ratios were used to separate the background charcoal. While at Borheen, Cuckoo, Diheen and Sheheree residuals were used. A similar number of fire events were identified using both methods at 4 of the study sites; the peaks at 2 sites Borheen and Sheheree Lough could not be identified using ratios, and Kelly's Lough produced a significantly larger number of events using the ratio method. This infers that the charcoal identified at the majority of sites was accumulated through multiplicative processes i.e. the total amount of charcoal introduced from a local fire is some multiple of background charcoal. Whereas the charcoal at Borheen and Sheheree Lough was accumulated through additive processes i.e. the charcoal introduced from a fire is added to the total amount of background charcoal. As determined by the ensemble member analysis the moving window varies depending on the charcoal distributions. This is to account for variance in the charcoal record, as selecting a threshold based on the entire series could lead to a bias of large or small peaks, whichever is dominant. Similarities in the charcoal identified can be seen across a number of sites; Borheen and Sheheree show the lowest amount of charcoal with median values of 0.002 and 0.004 pieces cm^{-2} yr^{-1} respectively. Cornaher and Cuckoo Lough also display similar median values of 0.027 and 0.011 pieces cm^{-2} yr^{-1}. The largest amount of charcoal was identified at Kelly's Lough with a median value of 0.83 pieces cm^{-2} yr^{-1}. This is comparable with a median value of 0.35 pieces cm^{-2} yr^{-1} at Ballinderry Lough and 0.16 pieces cm^{-2} yr^{-1} at Diheen Lough. A differing number of fire events are identified at each site here, ranging from 10 events at Diheen Lough to 3 events at Cuckoo and Sheheree Lough. The frequency and magnitude of events identified is function of the charcoal identified from the lake sediment. There is a lack of previous studies of fire history within Ireland and no information is available on regional patterns of wildfire. The fire regimes identified

show considerable variation between study sites, and it is clear that localised fires are specific to each site. It should be noted that not all peaks in charcoal represent fire events; as discussed the fire events are determined by a decomposition approach and threshold determination. CharAnalysis provides a wealth of information based on the charcoal data input, including identification of specific fire events, fire return intervals, fire frequency and fire magnitudes. It provides an output file of the CharAnalysis data and 10 figures displaying the results of the analysis. It provides the most current and accurate reconstruction of fire history, and has been widely accepted by experts in the field, and has been used with confidence here to produce detailed records of past fire regimes.

Fire Frequency

Fire frequency can be calculated as part of the CharAnalysis program; the total number of fires within a pre-defined window are summed and then the series is smoothed using a Lowess smoother (Higuera, 2009a). While this is a valid method for calculating fire frequency, a new method has been presented which calculates palaeo-fire frequency using a Gaussian kernel. This new method computes bootstrapped confidence intervals around the fire frequency curve, and provides a useful visual representation of how fire was behaving throughout the Holocene, and how fire increases and decreases over time. The calculations are carried out within Matlab, therefore some proficiency in Matlab is required. The analysis can be carried out quickly and accurately and provides a useful method of comparison between sites in this analysis. Both methods produce similar fire frequency curves at each of the study sites, indicating that the data are robust and both methods provide valid reconstructions. A number of sites display similar fire frequency curves; Cuckoo and Sheheree Lough both located in Killarney National Park, display fire events at the bottom of their record and one latter fire event towards the top of the record. Borheen and Diheen lough both display a concentration of fire events towards the present day, with a linear trend

in fire frequency at this point. The remaining study sites at Ballinderry, Cornaher and Kelly's lough display significantly different fire frequencies, which are dependent on the distribution and number of fire events throughout the record. The study sites display varying temporal scale and this should be considered when interpreting their fire frequency. Average fire frequencies are similar for the majority of study sites; Borheen (0.0004 fire.yr^{-1}), Cuckoo (0.0002 fire.yr^{-1}), Kelly's (0.0005 fire.yr^{-1}) and Sheheree Lough (0.0003 fire.yr^{-1}). Cornaher Lough displays a slightly higher fire frequency than these with 0.0007 fire.yr^{-1}. The highest average fire frequency was observed at Ballinderry and Diheen Lough with values of 0.007 fire.yr^{-1} and 0.01 fire.yr^{-1} respectively. These results suggest that there is a similar occurrence of fire at the majority of sites, with a slightly higher frequency at Cornaher, Ballinderry and Diheen Lough. Fire frequency provides an additional method of comparing fire regimes between sites and can therefore help to highlight significant commonalities.

Signal to Noise Index

The signal to noise index evaluates whether a charcoal record is appropriate for peak detection. Two methods of calculating the signal to noise index were adopted here; the first method is calculated as part of the CharAnalysis program and based on the equation outlined by Higuera (2009a) in Section 4.3.5. The second method outlined by Kelly et al. (2011) has a more complex equation also outlined in this section. This second method is carried out within R and a working knowledge of the R environment is necessary. The interpretation of the signal to noise index should be approached with caution, using Higuera's method a SNI>~0.5 is sufficient to warrant peak analysis, whereas a SNI>3 is preferable using Kelly's method. These methods must be viewed as a post hoc tool for evaluating charcoal records within a given threshold, and cannot be used as a basis for threshold selection. It is also important to note that SNI simply measures the separation between predefined S and N

populations, and cannot be considered to accurately quantify the trade-off between identifying local fires and minimizing the number of false positives (Kelly et al., 2011). Also a low signal to noise index does not necessarily mean that local fires are not correctly identified, or vice versa. It may simply mean that the peaks cannot be confidently considered distinct from the noise. It is also possible for distant fires or erosion events to create inaccuracy within the record by producing a high SNI. It is therefore important to take these considerations into account when interpreting the SNI and ideally use this analysis in conjunction with other parameters for increased accuracy. The SNIs were calculated using both methods for each of the 7 study sites in this analysis, the methods were executed relatively easily and only one record, Ballinderry Lough, posed a problem which required further interpretation. The signal to noise index calculated for this site via Kelly's method produced a value of 0, indicating that none of the signal samples exceed the specified threshold. This is however not true for Higuera's method where an average SNI of 9.1 was produced, and it is clear from the CharAanlysis results and identified fire events that there are instances where the signal exceeds the noise threshold. Further examination of the data has not yielded an explanation of the resulting zero value but there has been some discussion in relevant literature as to what affects the signal to noise calculations. Brossier et al. (2014) carried out a study to examine the effect of the width of the smoothing window to calculate background noise, on the SNI calculation. Results suggest using the smallest window width yielding a SNI>3 as a larger smoothing window reduces the SNI. It is also cautioned however that the goal of fire history reconstruction is not to maximise the SNI and parameters appropriate for each record should be chosen in light of the charcoal sampled. The SNI is also affected by choice of threshold which can lower the SNI calculation, especially when using the Gaussian mixture model (Kelly 2011). The signal to noise indices calculated for the rest of the study sites all exceeded the critical values outlined for at least part of their records. In

light of these analyses the SNI should be interpreted with caution and ideally in conjunction with other parameters; a low SNI does not always mean that the record is invalid and therefore should not be the sole focus of reconstructions.

Charcoal Area Peak Screening

A significant development in the charcoal analysis toolkit is the introduction of the charcoal area peak screening test. It applies a test similar to the minimum-count peak-screening (Gavin et al., 2006) carried out within CharAnalysis, but one appropriate for charcoal area data. The analysis is carried out in R using a script called ARCO for Charcoal Area Counts (Birks et al., 2012, Blaauw, 2010). The method screens charcoal area peaks identified through the CharAnalysis programme to guard against interpreting potential insignificant peaks as fire episodes. The set up and running of this analysis may be challenging for an inexperienced R user; it requires four input files for each set of data and caution should be taken with regard to the labelling and order of the columns. The analysis also requires detailed charcoal data not previously utilised by any other program. It requires an input file containing the surface area of each individual charcoal particle at each sample depth, which can result in a vast number of data points and be time consuming to generate. This fact also restricts the use of older data sets where this information may not be available, and in the case of this study, this applies to the Kelly's Lough data. It also restricts the data to studies carried out using the digital method of charcoal counting, as it is not feasible to quantify the surface area of each individual charcoal particle within a sample under the microscope. When executed however this method is useful in guarding against accepting 'false' charcoal peaks as fire episodes i.e. peaks which may have arisen spuriously from insignificant variations in charcoal area measurements. This method also provides a comparison between the C_A and Cfire-episode reconstructions, which can aid in the choice between the two

parameters. Alternatively both records may be found to be equally suitable, and both retained to form a 'consensus' reconstruction (Birks et al., 2004). When applied to the charcoal data in this study the analysis appears to work well, identifying the majority of fire events at each site as 'real fire events'. Only one site Ballinderry Lough failed to identify any fire events as 'real fire events', and is perhaps related to the low signal to noise index described previously for this site. Therefore there may be a link here in the effectiveness of this analysis with a low signal to noise index. Ultimately this analysis provides an important step towards the understanding of the relative strengths of the two different reconstructions. With the advancement in digital charcoal counting, yielding the required data, Finsinger et al. (2014b) recommends that the peak screening procedure be used whenever a fire-history reconstruction based on charcoal area measurements is published. It provides an important additional level of statistical accuracy to the identification of fire events within the charcoal record.

In review of the analysis and new techniques presented here, the fire events identified from each of the study sites can be accepted with confidence. The only site which posed a problem was Ballinderry Lough; reporting a value of 0 for the signal to noise index using Kelly's method. This in turn had a knock on effect for the charcoal peak screening from this site. As suggested in the literature, the signal to noise index should be interpreted with caution, and as Higuera's method produced an adequate signal to noise index of 9.1; the events identified at this site have been accepted. All fire events identified at each site have been included in the analysis in subsequent chapters, and have not been filtered by the charcoal peak screening. This is to aid a comparison with many previous charcoal studies from outside Ireland which utilise the CharAnalysis program, and predate the new charcoal peak screening method.

4.7 Conclusion

This chapter has provided a detailed reconstruction of past fire regimes at 7 study sites in a variety of locations in Ireland, and has utilised lacustrine sediment and macroscopic charcoal to identify significant fire events within the record. The latest methods and techniques in fire history reconstruction have been used and the fire regime reconstructions produced can be accepted with added confidence, as a variety of statistical tests and procedures have been employed to ensure a comprehensive analysis of the charcoal data. This study comprises the first chronological comparison of regional fire activity in Ireland, and a number of conclusions can be drawn;

1. Digital charcoal counting has been tested and is recognised as a valid method for identifying charcoal at sites within Ireland.

2. CharAnalysis provides a valuable and accurate tool for analysing sedimentary charcoal records from Ireland.

3. The identified fire events, their magnitude and frequency varies significant between the 7 study sites examined.

4. Study sites in Ireland represent different fire regimes with varying fire characteristics.

5. New methods such as ensemble member analysis and charcoal peak screening appear to be valid in charcoal analysis here.

6. Signal to noise calculations should be calculated and interpreted with caution as a measure of how appropriate a record is for CharAnalysis.

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Chapter 5

Comparing Patterns of Wildfire in Ireland with Regional and Global trends in fire history.

Abstract

In recent years a number of studies have suggested that trends in wildfire can be seen at a regional, national and global scale, and can be explained by interactions with factors such as anthropogenic activity and climate (Marlon et al., 2013, Liu et al., 2010, Bowman et al., 2009). As future susceptibility to fire is expected to be high (Flannigan, 2009, Girardin and Mudelsee, 2008) it is important to understand such interactions and drivers of fire to help manage and mitigate against its destructive impacts for the future. This chapter examines trends in wildfire within Ireland, between a range of study sites in both upland and lowland ecosystems. It provides a synthesis of the Irish charcoal record which is compared to trends from the UK, Europe, North America and the World to determine potential drivers of wildfire at a variety of geographical scales. A number of conclusions can be drawn that back up previous studies, suggesting climate and anthropogenic activities are significant drivers of fire at a variety of scales.

5.1 Introduction

Fire is a natural disturbance that occurs in most terrestrial ecosystems (Neary et al., 2005), it can have devastating impacts when its spread is large and unpredictable, however it can also be beneficial, especially when used as a management tool in certain ecosystems. Wildfire has

devastated areas of the US (Marlon et al., 2009) and Australia (Williams et al., 2001), and countries in Europe such as Spain (Pardini et al., 2004), Greece (Kalabokidis et al., 2007) and Italy (Salis et al., 2014). It affects all aspects of the ecosystem from the vegetation, soil, water and wildlife, to anthropogenic impacts and wider impacts on larger global systems. Wildfire has direct and important effects on the global carbon cycle, atmospheric chemistry, the hydrological cycle and overall catchment processes (Power et al., 2008). Global wildfire is dictated by factors such as climate, vegetation, humans and land use, which have been in fluctuation with the increase in atmospheric CO_2 and the onset of climate change (Prentice et al., 2011). In recent years with the increase in climate change there has been a wide concern for the implications this will have on wildfire (Westerling et al., 2006) with many hypothesising that wildfire will increase in the future (Girardin and Mudelsee, 2008), creating more frequent and intense impacts on the environment and people (McKenzie et al., 2004, Gonzalez et al., 2010). It is therefore important to study the interactions between fire and its controlling factors, as well as look to identify any patterns in wildfire that may exist regionally, nationally or even globally (Marlon, 2013).

At the beginning of the Holocene all continents except Antarctica were settled by humans (Marlon, 2013), providing a significant record to utilise in disentangling climate and human influences on changing fire regimes in various regions. The different anthropogenic and climatic histories of certain areas allow examination of fire interactions, which may simulate conditions similar to our own today or conditions which can be anticipated in the future. Palaeoenvironmental records extracted from sediment cores provide one of the best archives for information about the past landscape and climatic conditions (Last et al., 2001), allowing a chronological record of environmental changes to be uncovered. Charcoal fragments deposited within these sediment cores enable a charcoal record to be produced which reflects the fire history within the

surrounding landscape (Whitlock and Larsen, 2002). A number of studies have examined the relationship between sedimentary charcoal and its accumulation rate, deposition and source area to help clarify the distinction between background and peak charcoal for fire-history reconstructions. One such study by Marlon et al. (2006) in the USA confirms that background charcoal represents biomass burning which is a function of fuel characteristics, which are controlled by climate and vegetation. A later more in-depth study by Higuera et al. (2010) provides a method where area burned may be reconstructed from multiple charcoal records, highlighting that charcoal peaks represent 'local' fire history, and total charcoal accumulation may be utilised in composite records (Brubaker et al., 2009, Marlon et al., 2009, Whitlock et al., 2008) at larger scales to explore climate-fire linkages.

A number of studies have examined global trends in wildfire and identified that globally fire was low in the Late Glacial and Early Holocene subsequently increasing throughout the Holocene (Marlon, 2013, Power et al., 2008, Daniau et al., 2012). These trends are consistent with the global increase in temperature seen through the glacial-interglacial transition. However examining various regions, not all areas follow a similar pattern, presumably due to specific local conditions that were either conducive or unfavourable to fire. It can also be seen that changes in land use or human activity are not sufficient alone to explain the record of biomass burning at a regional or continental scale during the Holocene, although they do play a significant role at the local scale.

Over the past 150 years the global expansion of intensive grazing, agriculture and fire management have attributed to a decline in biomass burning (Marlon et al., 2008). This decline has occurred despite an increasing population and increasing air temperature. There was also a significant decline in biomass burning which occurred from AD 1 to ~1750 and has been attributed to a global cooling trend, with the subsequent

rise being linked to increasing human influences such as population growth and land use change (Marlon et al., 2008).

It has also been suggested that changes in CO_2 can reflect changes in biomass burning. Carcaillet et al. (2002) provided one of the first syntheses of continental scale palaeofire data examining the interaction of fire and atmospheric CO_2, suggesting that there has been a parallel increase in CO_2 and biomass burning since the Last Glacial Maximum. This is also supported by Jacobson (2004) who hypothesised that there will be a net accumulation of atmospheric CO_2 from biomass burning over time, taking into account the release of carbon post-fire due to vegetative regrowth. Both these studies also suggested that fire during the Holocene was driven by humans, with the evidence for intensified land use and anthropogenic activity. Similarly Ruddiman (2003) has argued that human use of fire for land clearance explains the increase in CO_2 and CH_4, having a significant impact on climate during the early/mid-Holocene. More recently Calvo et al. (2014) has stated that changes in CO_2 concentration are a major factor in changing global fire patterns, especially between glacial and interglacial periods. It should also be noted that fire risk could increase in areas that did not experience increased warming during the Holocene because the direct impact of rising CO_2 on vegetation productivity could increase fuel loads in these areas (Calvo et al., 2014).

Human activity is an important factor that could potentially affect global fire regimes. The term 'Anthropocene' is being increasingly used to represent concern regarding the large scale environmental change being driven by human activity (Chin et al., 2013, Oldfield et al., 2014). And a number of studies have been carried out to examine the relationship between the theory of an Anthropocene and global biomass burning (Ruddiman, 2005, Glikson, 2013, Bowman, 2014), as a key feature of the Anthropocene is the combustion of carbon rich fuels by humans i.e. fire activity. Considerable debate has existed as to what should be classed as

the beginning of the Anthropocene. Ruddiman (2013) proposed the 'early Anthropocene hypothesis' where humans began to alter global climate around 8000BP with the introduction of agriculture. The original concept places the Anthropocene at the beginning of the industrial revolution around 1780, when burning fossil-fuel rapidly increased greenhouse gas concentrations above background levels. More recently Glikson (2013) has proposed a three-staged model: early Anthropocene representing when hominins started using fire from at least >1.8 million years; mid Anthropocene representing the beginning of Neolithic agriculture c. 5000 years ago; and late Anthropocene representing the start of the Industrial Revolution. Others have adopted a deliberately imprecise period 'Palaeoanthropocene' to capture hominin (human and our ancestral species) impacts on the Earth System (Foley et al., 2013). Attempts to interlink fire activity and the Anthropocene have resulted in a series of main conclusions; biomass burning was increasing throughout the Holocene until very recently (Marlon et al., 2013) an increase in burning occurred from 12-10,000BP as a consequence of deglaciation and an increase in global temperatures. A further increase in burning occurred from 3-2,000BP, with no global forcing visible, the cause is thought to be related to an increase in aridity in the tropics and the rapid expansion of agriculture.

However there is no shift in global biomass burning corresponding to the early-Holocene increases in CO_2 or CH_4, and thus the charcoal records do not appear to support the Early Anthropocene Hypothesis. A number of modelling experiments have been carried out to examine the link between land use changes and changes in atmospheric composition during the Holocene e.g., (Joos et al., 2004, Vavrus et al., 2008, Kutzbach et al., 2010). The results from these studies suggest that humans appear to have exerted a substantial influence on global climate prior to the industrial era, accounting for one third of the change in greenhouse gas forcing.

During the past two centuries, anthropogenic activities dominate the global biomass burning signal (Marlon et al., 2012), and factors such as population growth, fire suppression, land use change, agriculture, overgrazing, urbanisation and invasive plants, have caused changes in fire regimes (Bowman et al., 2011). There is no straight forward way to distinguish between human and natural wildfires within the palaeo-record, we must rely on the synchronicity of events with indicators of human activity (Marlon, 2013). Evidence from archaeological sites can shed light on human presence and activity within an area. We can also gain knowledge from the vegetative record, looking for species which indicate farming practices (i.e. Cereal-type, *Triticum*), large declines in taxa which may indicate clearance (e.g. tree species), or other taxa which may indicate an anthropogenic influence in the landscape (i.e. *Plantago lanceolata, Rumex species*. and *Artemisia*). In order to try and separate climate and human impacts it is necessary to access the synchrony of environmental changes (Gavin et al., 2006, Ali et al., 2009). This is based on the theory that similar patterns of disturbance are unlikely to occur over a range of sites, in a variety of locations, unless driven by a factor on a similar scale such as climate (Haberle and Ledru, 2001). This is however conflicted with intercontinental innovations such as Bronze Age and Iron Age activity, which can occur on similar timescales. Comparisons of the charcoal record can be made between individual sites within a region, or between composite charcoal records on a national or global scale, and can be used to explore the interactions between wildfire, humans, vegetation and climate in a variety of ecosystems.

Two pioneering studies involving charcoal synthesis (Haberle and Ledru, 2001, Carcaillet et al., 2002) have established that there are inter-hemisphere linkages in palaeo-fire activity on a millennial timescale (Power et al., 2008). There have been a number of further studies which utilise the Global Charcoal Database (Power et al., 2010) for a charcoal data synthesis, in an attempt to understand interactions with fire,

vegetation and climate at the global scale (Marlon, 2013, Daniau et al., 2012, Power et al., 2010, Power et al., 2008, Marlon et al., 2008).The results of these studies when considered globally can be summarized in three main conclusions; (1) There has been a monotonic increase in biomass burning since the Last Glacial Maximum and (2) there has been a shift from low to high spatial heterogeneity in fire activity from approx. 12,000BP. Finally (3) the interactions between fire, vegetation, climate and people are complex and require further study on a variety of temporal and spatial scales.

Further similar studies were carried out at a regional scale (Marlon et al., 2009, Mooney, 2011, Vannière et al., 2011, Power et al., 2013), which give insights into regional controls of wildfire. Charcoal comparisons such as these were obtained by applying several analytical steps using a set of Fortran programs (Bartlein, unpublished), which are not easily modifiable or usable. Hence a statistical package, 'Paleofire' has been developed in R, by the Global Palaeofire Working Group, which utilises data from the Global Charcoal Database, as well as a function to input your own data, with the goal of transformation, interpolation and synthesis (Blarquez et al., 2014) of charcoal data to examine biomass burning and its interactions at a potentially global scale.

This chapter presents a comparative analysis of wildfire between 7 study sites spread across Ireland, in an attempt to identify any regional trends which may exist, and examine how these trends tie in with wildfire at a European and global scale. This is the first analysis of its kind in Ireland, and the record of past fire regimes is largely unknown. Ireland's unique location as an island on the edge of Europe provides the perfect backdrop to study oscillations in past environments, climate and extreme events. Future climate predictions for Ireland indicate that temperatures are to continue to increase, and summers are to become drier with up to a 20% reduction in precipitation (Gleeson et al., 2013). This will increase the vulnerability of the Irish landscape to wildfire, therefore studies such as

this are essential to identify and quantify the drivers and patterns of wildfire in Ireland in the past, which will help to predict and manage the future impacts of wildfire.

This analysis uses a number of statistical tests to quantify the relationships identified between the study sites in Ireland in a comparative analysis. A composite record of fire history is also produced using the 'Paleofire' package, to represent Ireland and this is compared to composite records from the UK, Europe, North America and the Globe, utilising data from the Global Charcoal Database, to try and identify any common trends in wildfire. This analysis will yield further information about the drivers of wildfire, how wildfire changes over time, and its response to current climatic changes, on a local and global scale.

5.2 Aims

1. Examine the charcoal record from each of the study sites in a comparative analysis of wildfire in Ireland.

2. Create a composite record of fire history for Ireland and compare this to the composite records from UK, Europe, North America and the World.

3. Carry out a variety of statistical tests to quantify the relationships outlined in the comparative studies.

5.3 Study Sites

All seven study sites (discussed in detail in Chapter 3) are included in this comparative analysis. Additional charcoal data are utilised from the Global Charcoal Database (v. 2) (Power et al., 2010) to aid in the composite analysis, it holds charcoal records from a total of 1105 study sites, differing considerably in site type and location (Power et al., 2010).

The charcoal data from Ireland was generated from lacustrine sediment hence; only lake sites from the GCD were chosen for comparison in this study, and grouped into different regions depending on location i.e. UK, Europe, North America and Worldwide. The charcoal and dating methods vary between sites within the GCD, and detailed metadata are available for each site including dating technique, chronology, site type and charcoal method (Power et al., 2008). Some variation is accounted for in the data analysis via transformation and scaling to a constant temporal interval.

5.4 Methods

To generate the Irish charcoal data presented, charcoal analysis was carried out on the sediment cores from all sites and the method for preparation is adapted from those described by Mooney and Black (2003) and Mooney and Radford (2001). Digital image analysis using Image J was applied once the samples were prepared, to generate count and area data, and follows methods similar to Schlachter (2012). Each of the sediment cores was also radiocarbon dated, and an accurate chronology was produced using BChron and Intcal13 calibration curve (Haslett and Parnell, 2008). As described in Chapter 4 numerous statistical methods were used to analyse and validate the charcoal record presented. CharAnalysis (Higuera, 2009) a programme within Matlab was used to identify specific fire events, their magnitude, fire frequency and fire return interval. Specific parameters for this analysis were chosen in conjunction with an Ensemble Member strategy (Blarquez et al., 2013). and the identified fire regime analysed using a signal to noise index (Kelly et al., 2011), goodness of fit (Blarquez et al., 2013) and charcoal peak screening method (Finsinger et al., 2014). All the fire events identified via the CharAnalysis programme have been included in the comparative analysis in this chapter, despite a number of them not passing the charcoal peak screening method, and deemed as robust fire events. The

charcoal peak screening method is still a new concept in charcoal analysis and to allow ease of comparison with previous studies which widely accept the CharAnalysis method for identifying fire events, all identified fire events have been included. Prior to statistical analysis the charcoal data from each study site were tested for normality using a Q-Q Plot in R and a Shapiro-Wilk normality test. All sites rejected the null hypothesis i.e. the data follow a normal distribution, with p values significantly less than 0.05. Transforming the data using logs proved ineffective therefore the subsequent analysis uses a series of non-parametric tests. The methods below present an interpretive and statistical comparison using appropriate methods to examine the charcoal data at each of the study sites.

5.4.1 Fire Event Comparison

To aid a comparison of fire events occurring at a similar time scale at various sites, the study sites were divided into two groups depending on the length of the record and the nature of the fire events identified. The fire events at Ballinderry, Borheen, Diheen and Kelly's Lough (Group A) are compared and can be seen plotted in Figure 5.1 covering the time period from the present day to 2000BP. Cornaher, Cuckoo, Kelly's and Sheheree Lough (Group B) are also compared and their charcoal distributions and fire events can be seen in Figure 5.2 covering the remaining part of the record from 2000BP-17000BP. Kelly's Lough was included in both comparisons as the record here spans 11,000 years and has fire events spread throughout the record. Study sites are omitted from either group when no fire events are identified in that part of their record.

5.4.2 K-S Test

A two sample Kolmogorov-Smirnov Test was used to analyse whether two charcoal distributions are the same, or significantly different from one another. It assumes independent values, unpaired data and non-Gaussian distributions. The analysis is carried out in R and identifies whether two distributions differ significantly not only by mean but also by variance. The k-s test was used to compare all study sites within specific archaeological time periods (outlined by the Department of Arts, Heritage and the Gaeltacht), which are outlined in Table 5.1. The Char distributions were interpolated to a constant time interval of 15 years to make the data more comparable. The data were then divided into the different time periods (note: not all charcoal distributions cover all time periods), and the test statistic applied. Two distributions were deemed significantly different from one another if $p<0.05$. The k-s test was also applied to the composite data from Ireland, UK, Europe, Northern USA and the World in a comparative analysis.

Table 5.1 Dating of Archaeological time periods for use in comparative analysis between study sites.

Archaeological Time Period	**Age (BP)**
Palaeolithic	Pre 10,000
Mesolithic	10,000-6,000
Neolithic	6,000-4,400
Bronze Age	4,400-2,500
Iron Age	2,500-1,600
Medieval Period	1,600-300
Modern	300-0

5.4.3 Weibull Likelihood Ratio Test

Fire Return Intervals

The likelihood ratio test is used here to compare two populations of fire return intervals; it relies on a test statistic, T, computed by taking the ratio of the maximum likelihood estimate both under the constraints of the null hypothesis and when the constraints are relaxed (in Matlab; (Clark, 1989, Johnson and Gutsell, 1994, MathWorks, 2005). The null hypothesis can be expressed as H_o : $b_1 = b_2$ AND $c_1 = c_2$ and is tested against its alternative H_a : $b_1 \neq b_2$ OR $c_1 \neq c_2$, where b and c are the maximum likelihood estimates for the scale and shape parameters, respectively, for each hypothesised population (1,2...n). The log-likelihood function for the two-parameter Weibull transformation and the test statistic for the likelihood-ratio test, T can be seen below as a) and b) respectively.

a) $$l = \log L = \log \prod_{i=1} f(b,c|t_i) = \sum_{i=1}^{n} \log f(b,c|t_i)$$

b) $$T = 2(l_{H_1} - l_{H_0}) = 2(l_{1H_1} + l_{2H_1} - l_{H_0})$$

The significance level of the test, alpha, was defined as P≤0.05 and the number of permutations was defined as n_perm=1000. This is the number of permutations to use in the permutation test to estimate the probability of Type 1 error. The null hypothesis is rejected if P≤0.05. The test also returns values of 1 or 0 which correspond to rejecting or failing to reject the null hypothesis, respectively. The distribution of fire return

intervals (years per fire; FRIs) within each archaeological period at each study site were used in a comparative analysis utilising the Weibull Likelihood ratio test. The null hypothesis i.e. FRIs did not differ between sites, was tested based on estimates of the Weibull b and c parameters. By utilizing both parameters of the Weibull distribution, the LRT provides a more powerful method for detecting difference in FRI distributions than possible by interpreting confidence intervals around the mean or median FRI and estimated Weibull statistics (e.g., (Clark, 1990, Lynch et al., 2002)) or by using the nonparametric K-S test (Lynch et al., 2004, Anderson et al., 2006, Gavin et al., 2006).

Peak Magnitudes

The Weibull likelihood ratio test was also used to compare the magnitudes of fire events, between sites within the specific archaeological time period, and follows a similar method as outlined above. The null hypothesis here is the magnitude of fire events does not differ between sites within each respective archaeological time period. The null hypothesis is rejected if $P \leq 0.05$ and the test statistic returns a value of 1. As a large volume of comparisons are carried out only significant results will be presented.

5.4.4 Charcoal Synthesis

The Paleofire package within R (Blarquez et al., 2014), is used here for the analysis and synthesis of charcoal data from the 7 study sites discussed above, and the sites selected for analysis from the Global Charcoal Database (GCD). The required data are loaded into the package and assigned a code (e.g. mydata) for easy accessibility. Charcoal values from the GCD and from the charcoal data identified previously can vary widely within and between sites due to multiple factors such as charcoal

accumulation, varying analytical methods or type of record. To try and account for this, the charcoal records were standardised before generating any composite record (Power et al., 2008). A three step data transformation was employed which includes a minimax data rescaling, a variance homogenization using a Box and Cox (1964) data transformation, and a final rescaling to Z-scores. In this analysis another minimax rescaling was added after the Box-Cox transformation because Box-Cox transformed series are only comparable if they share identical λ values (Marlon et al., 2008). A synthesizing or compositing is carried out whereby the charcoal data from each of the selected sites are pooled to calculate a mean charcoal value across all sites at each time step. The composite curve is calculated using a data-binning procedure, where the mean charcoal value is calculated within each binning interval (500-years) and then the mean calculated for the whole series (Blarquez et al., 2014). The composite approach used here is similar to that of Power et al. (2008), but also combines methods proposed by Marlon et al. (2008) and Daniau et al. (2012). Confidence intervals associated with the composite curve were calculated using a bootstrap resampling of the binned charcoal series and the mean calculated for each bin 1000 times i.e. nboot=1000. The method and parameters used here have been chosen to produce a composite record, as accurate as possible for the study sites in question. Caution should however be taken when interpreting the curve where the number of study sites is low e.g. before 10,500BP.

5.4.5 Kruskal-Wallis Test

The Kruskal-Wallis test is a one-way analysis of variance by ranks, and is a non-parametric method testing whether samples are significantly different from one another. This test can be carried out on two or more sets of independent data with varying sample size. This test was carried

out on the charcoal data between the archaeological time periods identified at each of the study sites, as a comparative analysis in R. The charcoal data were interpolated to a constant time interval prior to analysis to aid comparison. The null hypothesis states that the mean ranks of the groups are the same, and if the resulting p value is greater than 0.05 then the null hypothesis is accepted. These tests simply reveal if there is a difference between any of the records associated with each of the defined archaeological periods, and does not indicate which relationships are significant. For this a multiple comparison kruskalmc test is carried out in R, both on the charcoal data from each individual study site and on the composite data.

5.5 Results

5.5.1 Fire Event Comparison

Group A (Ballinderry, Borheen, Diheen and Kelly's Lough)

Four study sites are compared here examining the distribution of identified fire events, on a temporal scale ranging from the present day back to 2000BP. Seven fire events were identified at Ballinderry Lough and are concentrated between the present day and 1050BP. This site is similar to the record from Diheen Lough where all the fire events are located in the first half of the record from 800BP towards the present day. This is in contrast to the record from Kelly's Lough, where the fire events are located in the second half of the record from 1600-2000BP. While the five fire events identified at Borheen Lough are spread rather evenly throughout the entire record from 0-2000BP. Looking at Figure 5.1 a number of fire events can be seen to occur at a similar temporal scale. At the beginning of the record there are three fire events which coincide at Ballinderry, Borheen and Diheen Lough, with ages of 103BP, 95BP and 159BP respectively, and varying magnitudes of 492cm^{-2} $peak^{-1}$,

0.6cm^{-2} peak^{-1} and 3.4cm^{-2} peak^{-1} These events are closely spaced and may be a reflection of a common influencing factor. Borheen and Diheen Lough are located in adjacent catchments within the Galty Mountains, while Ballinderry is located in the lowland Irish midlands. Moving further down the record there are two events which occur at a similar time at 373BP at Ballinderry Lough and 395BP at Diheen Lough, with magnitudes of 0.98cm^{-2} peak^{-1} and 5.2cm^{-2} peak^{-1}. Other similar events that occur within this time period are at Borheen Lough, dated to 607BP (magnitude: 4.89cm^{-2} peak^{-1}) and slightly earlier at 595BP (magnitude: 0.16cm^{-2} peak^{-1}) at Diheen Lough, and a later event at 616BP (magnitude: 0.15cm^{-2} peak^{-1}) at Ballinderry Lough, suggesting that similar conditions prevailed across all the sites at this time. Borheen and Kelly's Lough also have two similar events occurring at 1616BP (magnitude: 1.36cm^{-2} peak^{-1}) and 1778BP (magnitude: 9.27cm^{-2} peak^{-1}) at Kelly's Lough and 1519BP (magnitude: 0.71cm^{-2} peak^{-1}) and 1711BP (magnitude: 0.35cm^{-2} peak^{-1}) at Borheen Lough. Both these sites occur in upland environments, Borheen Lough in the Galty Mountains and Kelly's Lough in the Wicklow Mountains.

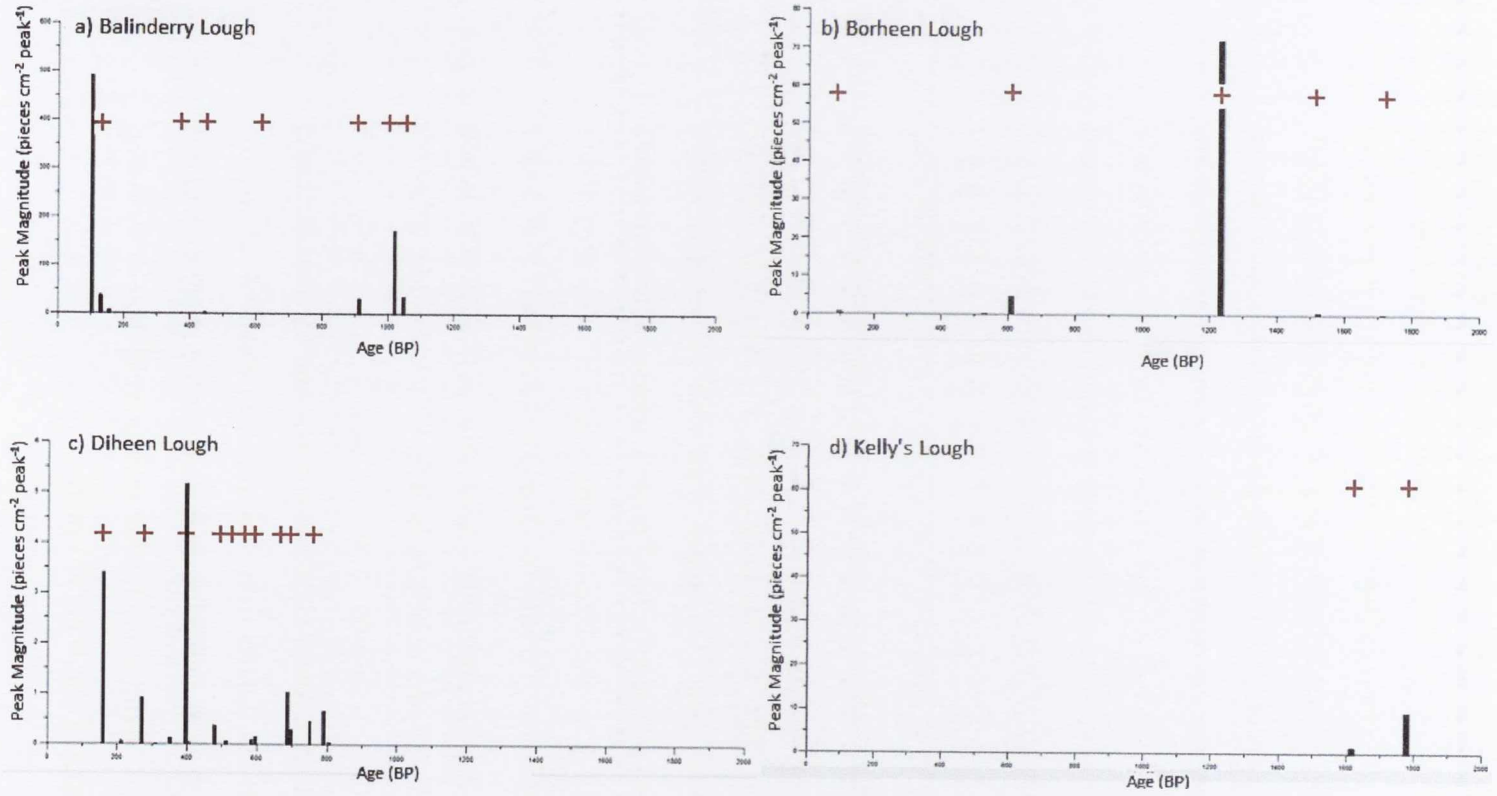


Figure 5.1 Group A Comparison of Fire Events (red crosses) and Fire Magnitude (black bars) at a) Ballinderry Lough, b) Borheen Lough, c) Diheen Lough and d) Kelly's Lough.

Group B (Cornaher, Cuckoo, Kelly's and Sheheree Lough)

A comparison was carried out on the identified fire events between Cornaher, Cuckoo, Kelly's and Sheheree Lough for the remaining part of the record from 2000BP-17500BP. Eight fire events identified at Cornaher Lough are located in the first half of the record from 2,000BP-10,000BP, with a cluster of fire events concentrated around approx. 3500BP. This is similar to the record at Kelly's Lough in that all three fire events occur in the first half of the record i.e. between 2000BP and 6000BP here. A similar number of fire events are identified at Cuckoo and Sheheree Lough, with four and three events respectively. The events at Cuckoo Lough are predominantly located at the bottom of the record with three events concentrated from approx. 16300-17500BP. The events at Sheheree are spread in a similar trend with one event located at 3879BP and the other two between 9700-10,000BP. Both these sites are located within Killarney National Park. The event at 3879BP (magnitude: 408.9cm^{-2} $peak^{-1}$) is similar to an event occurring at Kelly's Lough at 4136BP (magnitude: 75.7cm^{-2} $peak^{-1}$). Looking at the fire events identified in Figure 5.2 for the Group B comparison of study sites, fewer fire events coincide compared with the Group A comparison. The closest events that occur in this group are at Cornaher and Sheheree Lough where there are fire events occurring at 9751BP (magnitude: 25.4cm^{-2} $peak^{-1}$) and 9752BP (magnitude: 1.78cm^{-2} $peak^{-1}$) respectively. Both these sites are located at lower elevations of 91m and 65m respectively; in comparison with the upland sites that are at an elevation of approx. 500m. Comparing the remaining fire events across the study sites in this group it is difficult to identify any further events which coincide closely, specifically with a gap of less than 100 years.

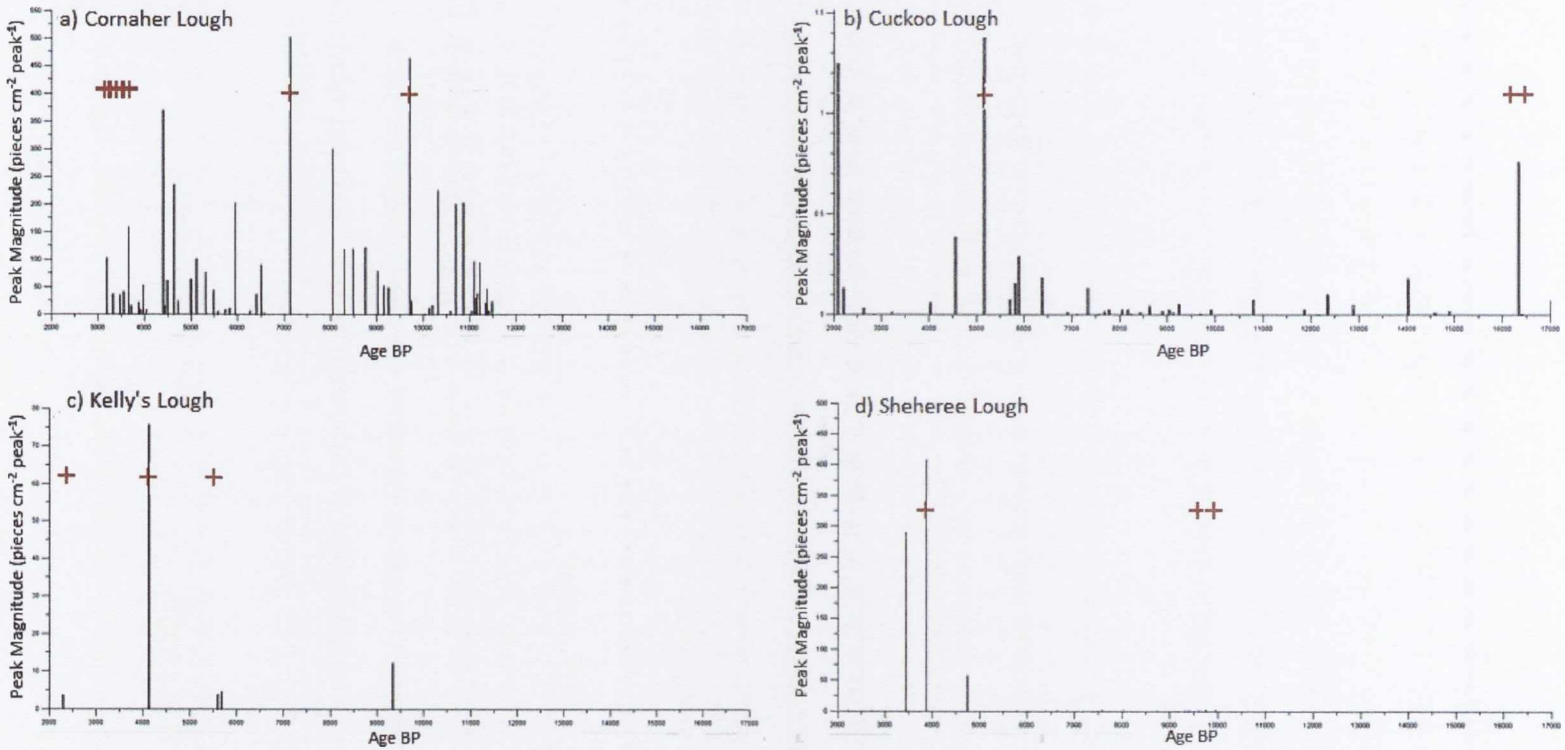


Figure 5.2 Group B Comparison of Fire Events (red crosses) and Fire Magnitude (black bars) at a) Cornaher Lough, b) Cuckoo Lough, c) Kelly's Lough and d) Sheheree Lough.

5.5.2 K-S Test

A two sample Kolmogorov-Smirnov Test is used here to analyse whether two series of interpolated charcoal concentrations are the same, or significantly different from one another. The data were interpolated to a constant time interval of 15 years and subsequently divided into archaeological time periods prior to analysis. The significant results from this analysis are presented in Table 5.2.

Palaeolithic Pre 10,000BP

Ten pair wise comparisons were carried out for this time period between five study sites; Borheen, Cornaher, Cuckoo, Kelly's and Sheheree Lough. The k-s test returned no significant results during any of the analysis. The highest p-value of 0.008264 was recorded between Cornaher and Cuckoo Lough with a test statistic of D=0.1808. All p-values recorded were below 0.05 meaning that all sites included in the comparisons are significantly different from one another.

Mesolithic 10,000-6,000BP

No significant results were returned from the k-s tests carried out in this time period between 5 study sites; Borheen, Cornaher, Cuckoo, Kelly's and Sheheree Lough. All p-values recorded were well below the 0.05 significance level, indicating that the charcoal records analysed from each site are significantly different from one another.

Neolithic 6,000-4,400BP

During this time period five study sites; Borheen, Cornaher, Cuckoo, Kelly's and Sheheree, were used in the k-s test comparisons. All p-values calculated here are below the 0.05 critical level, indicating that each study site is significantly different from its comparison. The highest p-

value=0.0288 was recorded between Cornaher and Cuckoo Lough with a test statistic of D=0.2019.

Bronze Age 4,400-2,500BP

Six comparisons were carried out here using the k-s test, between Borheen, Cuckoo, Kelly's and Sheheree Lough. The k-s test between Borheen and Cuckoo Lough produced a p-value of 0.1165 and a test statistic D=0.1496, indicating that the records are statistically similar. The remaining comparisons did not indicate any significant similarities between the records, and the remaining p-values are below the 0.05 significance level indicating that the study sites and their comparisons are statistically different.

Iron Age 2,500-1,600BP

During this time period six comparisons were carried out between Borheen, Cuckoo, Kelly's and Sheheree Lough using the k-s test. The comparison between Borheen and Cuckoo Lough produced a p-value of 0.07626 and a test statistic of D=0.2333, indicating that the records are statistically similar. The remaining p-values recorded here failed to indicate any similarity between the records from the rest of the study sites analysed. The p-values occur below the 0.05 critical threshold indicating that the charcoal records tested are statistically different from one another.

Medieval Period 1,600-300BP

Within this time period 15 pairwise comparisons were carried out between 6 study sites, Ballinderry, Borheen, Cuckoo, Diheen, Kelly's and Sheheree Lough. None of the 15 comparisons produced significant p-values above the critical value of 0.05, indicating that all the records are statistically different from one another. The largest p-values are associated with the comparisons between Borheen and Diheen Lough,

and Cuckoo and Sheheree Lough with p-values of 0.00098 and 0.00019 respectively.

Post Medieval-Modern 300BP-Present

The three pairwise comparisons carried out in this final time period are between the records from Ballinderry, Borheen and Diheen Lough. One record produced a p-value greater than 0.05, indicating that the record from Borheen and Diheen Lough are statistically similar, with a p-value of 0.8531. The remaining comparisons also produced high p-values compared to the other time periods, with values of p-value=0.0423 and p-value=0.0171 for the comparisons between Ballinderry and Diheen Lough, and Ballinderry and Borheen respectively. However these comparisons are below the 0.05 critical threshold and are not deemed statistically similar.

Holocene pre 10,000-Present

The entire charcoal records from each study sites were also compared against one another in a similar analysis. None of the comparisons produced a p-value greater than 0.05, suggesting that the overall records differ significantly.

5.5.3 Weibull Likelihood Ratio Test

Fire Return Intervals

The Weibull likelihood ratio test is used here to determine if there is a relationship between fire return intervals from the various study sites, with respect to the specific archaeological time periods. The null hypothesis that there is no difference between the two populations of fire return intervals is tested to a significance level of 0.05.

Palaeolithic Pre 10,000BP

The only site with fire return intervals occurring in this time period is Cuckoo Lough, therefore no comparisons were carried out here.

Mesolithic 10,000-6,000BP

Two sites have fire events occurring in the Mesolithic period and one comparison was carried out here between the fire return intervals at Cuckoo and Sheheree Lough. The sample size however was not sufficient to aid an appropriate comparison.

Neolithic 6,000-4,400BP

Only one site Cuckoo Lough has a fire return interval associated with this time period, therefore no comparisons were carried out here.

Bronze Age 4,400-2,500BP

Cornaher, Kelly's and Sheheree Lough have fire return intervals occurring in the Bronze Age period, and three comparisons were carried out here. All three comparisons however did not produce significant results, suggesting that the distribution of fire return intervals differs significantly between sites in this time period.

Iron Age 2,500-1,600BP

Only one site, Kelly's Lough has fire events and hence fire return intervals occurring within this period, therefore no comparisons could be made here.

Medieval Period 1,600-300BP

Using the Weibull likelihood ratio test 3 pairwise comparisons were made between 3 study sites; Ballinderry, Borheen, and Diheen Lough. Of

the 3 comparisons 2 produced H values of 0 indicating that the null hypothesis should be accepted and there is a significant relationship between the fire return intervals at particular sites. The same 2 comparisons also produced p-values exceeding the significance level 0.05. These comparisons were between Ballinderry and Borheen Lough, and Ballinderry and Diheen Lough, producing p-values of 0.1195 and 0.0845 respectively. This indicates that there is a relationship between the fire return intervals at these sites. The third comparison between Borheen and Diheen produced a p-value of 0.002, below the critical value of 0.05, therefore no relationship between the fire return intervals can be assumed here.

Post Medieval-Modern 300BP-Present

During this final period one significant comparison was carried out between Ballinderry and Diheen Lough. The Weibull likelihood ratio test produced an H value of 0 and a p-value of 0.0891. This p-value is above the significance level of 0.05, indicating that the null hypothesis should be accepted and there is a relationship between the populations of fire return intervals at both sites. Two other comparisons were carried out within this time period between Ballinderry and Borheen Lough, and between Borheen and Diheen, however an insufficient sample size meant the comparisons were considered invalid.

Holocene pre 10,000-Present

Looking at the fire return interval distributions for the entire Holocene and conducting a comparison between all of the study sites, a number of significant results are produced. The associated p-values can be seen in Table 5.3. The significant results highlighted in red, indicating that the null hypothesis should be accepted and there is a relationship between the fire return intervals at the two study sites. 21 pair-wise comparisons were carried out between the seven study sites, and 13 of them

produced results indicating a significant relationship between the fire return interval distributions. The most significant relationship was identified between Sheheree and Cuckoo Lough with the highest p-value of 0.786 in the analysis.

Peak Magnitudes

The Weibull likelihood ratio test was also used here to compare the magnitude of identified fire events. The results below are split into the archaeological time periods in which they were compared. The null hypothesis that there is no difference in the fire event magnitudes was tested to a significance level of 0.05.

Palaeolithic Pre 10,000BP

Three fire events occur within the Paleolithic period at Cuckoo Lough. No comparisons were carried out within this period as all fire events occurred at one site.

Mesolithic 10,000-6,000BP

Two study sites, Cornaher and Sheheree Lough have a total of 5 fire events which occur in the Mesolithic period. A comparison was carried out between the two study sites and the magnitudes of their fire events; however no significant result was produced, suggesting that there is no relationship between the magnitudes of fire events at each site.

Neolithic 6,000-4,400BP

Cuckoo and Kelly's Lough have two fire events occurring in the Neolithic period, and a comparison was carried out between the magnitudes of fire events at each site. The results did not produce any significant relationship between the magnitudes; this was due to the low sample size which was insufficient to compute the Weibull likelihood ratio test.

Bronze Age 4,400-2,500BP

During the Bronze Age seven fire events occurred between Cornaher, Kelly's and Sheheree Lough with varying magnitudes. The relationship between these was tested with three pairwise comparisons using the Weibull likelihood ratio test. No significant relationships were identified between the magnitudes of fire events at each site.

Iron Age 2,500-1,600BP

Four fire events occurred at Kelly's Lough during the Iron Age, but only one fire event at Borheen Lough. This was an insufficient sample size to warrant a Weibull comparison between the fire event magnitudes here.

Medieval Period 1,600-300BP

The medieval period appears to be the most active in terms of fire events. A total of 17 fire events were identified, spread across three study sites, Ballinderry, Borheen and Diheen Lough. Three comparisons of fire event magnitudes were carried out between each of the study sites, with one producing significant results. The comparison between Ballinderry and Borheen Lough produced a very high p-value of 0.942, above the critical value of 0.05 indicating that the two records are statistically similar. The remaining comparisons between Ballinderry and Diheen Lough, and Borheen and Diheen Lough produced p-values of 0.0046 and 0.0176 respectively. This indicates that the null hypothesis of no significant difference between the two distributions should be rejected.

Post Medieval-Modern 300BP-Present

From the post medieval to the present day there have been four fire events spread over three study sites, Ballinderry, Borheen and Diheen Lough. Ballinderry and Borheen Lough only contain one fire event each therefore the sample size is too small to warrant a comparison using the Weibull likelihood ratio test here.

Holocene pre 10,000-Present

A comparison using the Weibull likelihood ratio test was also carried out between all of the study sites, using the fire event magnitudes for the entire Holocene. Of the twenty-one comparisons carried out, fifteen returned significant results i.e. a p-value greater than the critical value of 0.05. The associated p-values can be seen in Table 5.4 with the significant results highlighted in red. The largest p-value produced was 0.937 and occurred between Ballinderry and Sheheree Lough, followed closely by the comparison between Diheen and Cuckoo Lough with a p-value of 0.931

Table 5.2 significant results from k-s test on interpolated charcoal concentrations.

Archaeological Period	Study Site Comparison	Test Statistic (D)	p-value
Bronze Age 4,400-2,500BP	Borheen vs Cuckoo	0.1496	0.1165
Iron Age 2,500-1,600BP	Borheen vs Cuckoo	0.2333	0.07626
Post Medieval-Modern 300BP-Present	Borheen vs Diheen	0.1905	0.8531

Table 5.3 p-values from Weibull likelihood ratio test on fire return intervals, values highlighted in red represented significant results.

Study Site	Borheen	Cornaher	Cuckoo	Diheen	Kelly's	Sheheree
Ballinderry	0.025	0.328	0.056	0.026	0.012	0.126
Borheen	NaN	0.191	0	0	0.228	0.308
Cornaher	NaN	NaN	0.506	0.068	0.198	0.503
Cuckoo	NaN	NaN	NaN	0.01	0.502	0.786
Diheen	NaN	NaN	NaN	NaN	0	0
Kelly's	NaN	NaN	NaN	NaN	NaN	0.541

Table 5.4 p-values from Weibull likelihood ratio test on peak magnitude, values highlighted in red represent significant results.

Study Site	Borheen	Cornaher	Cuckoo	Diheen	Kellys	Sheheree
Ballinderry	0.335	0.172	0.089	0.024	0.35	0.937
Borheen	NaN	0.015	0.678	0.356	0.485	0.724
Cornaher	NaN	NaN	0.003	0	0.045	0.301
Cuckoo	NaN	NaN	NaN	0.931	0.204	0.446
Diheen	NaN	NaN	NaN	NaN	0.025	0.197
Kelly's	NaN	NaN	NaN	NaN	NaN	0.5

5.5.4 Charcoal Synthesis

The charcoal records from all the study sites included in this analysis were transformed and synthesised into one record to represent Ireland. Using the Global Charcoal Database study sites were selected based on type i.e. lakes, and used to make similar composite records for the UK, Europe, North America and the Globe. The results below represent a comparison between the Irish record and the records extracted from the Global Charcoal Database.

Irish and UK composite charcoal comparison

For the composite record from Ireland, charcoal data from the seven study sites discussed in this thesis were used. Additional data were available from the Global Charcoal Database to create a composite record for the UK, which comprises eight data sets produced from lacustrine sediment. Using identical methods of transforming and synthesising the data, two composite records were produced for Ireland and the UK and can be seen in Figure 5.3. The two records show the same general increasing trend from approx. 15,500BP to the present day. There are a number of key trends that appear to occur within both the records. There are marked decreases in both records at 13,250BP and 4750BP. The earlier decrease is more extreme in the Irish record whereas the latter decrease is more pronounced in the UK record. Following similar trends to the UK record, the Irish record does exhibit a number of more extreme peaks, namely at 9750BP, 6250BP and 1250BP. Looking at the overall trend it could be argued that the Irish record is closely related to that from the UK, with trends reflected earlier in the UK record in certain places.

Irish and European composite charcoal comparison

The composite record from Ireland was also compared to the composite record for the whole of Europe and can be seen in Figure 5.4. Fifty-six charcoal records from lacustrine sediment were utilised from the Global Charcoal Database to calculate the composite record for Europe. This record also follows the general trend shown by the UK and Ireland, increasing from approx. 15,000BP towards the present day. Comparing the record from Europe to the Irish record, it appears smoother with less extreme peaks and troughs throughout the record. There are a number of marked decreases within

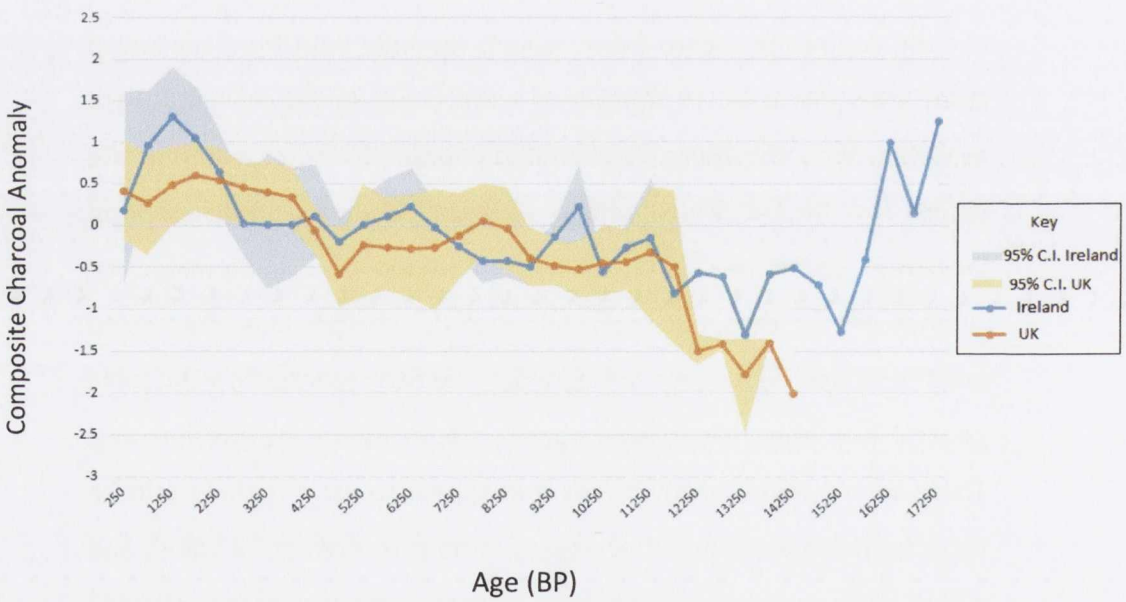


Figure 5.3 Comparison of composite charcoal records from Ireland and UK

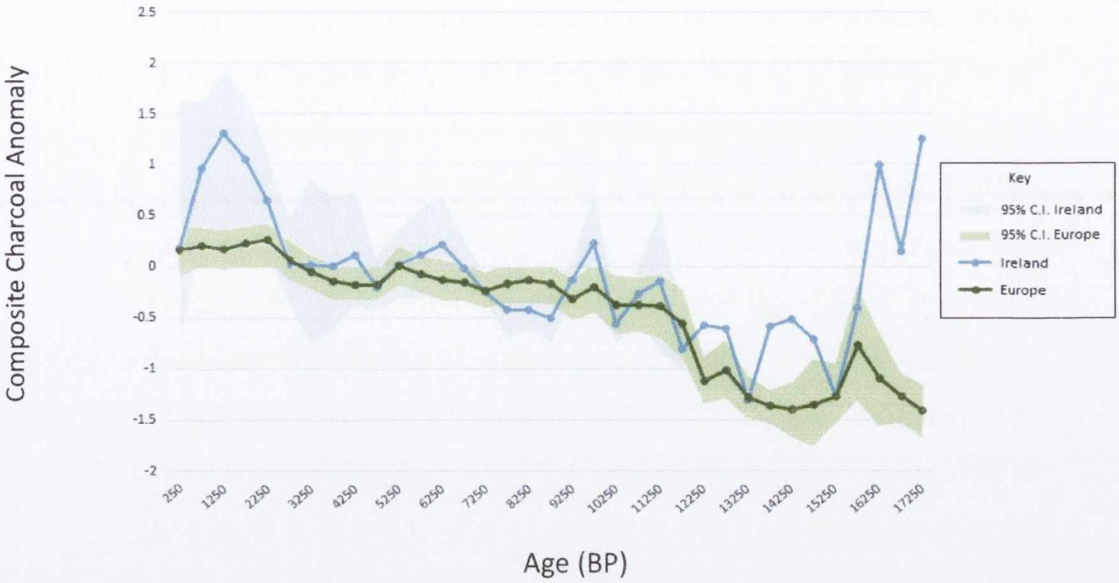


Figure 5.4 Comparison of composite charcoal records from Ireland and Europe.

the European record which occur just prior to a similar decrease in the Irish record. These decreases are evident at 12,250BP, comparable to a decrease at 11,750 in the Irish record, and at 9250BP, corresponding to a similar decrease in the Irish record at 8750BP. Both records show marked decreases, correlating at 15,250BP and 4750BP. A number of small peaks occur within the European record which coincides with larger, more pronounced peaks in the Irish record, occurring at approx. 16,000BP, 12,750BP and 9750BP. These two records therefore follow a similar general trend throughout, with comparable oscillations at various points, representing an increase or decrease in charcoal activity.

Irish and North American composite charcoal comparison

A composite record was created using charcoal data from 178 lake sites spread throughout North America. This record is compared to the composite record in Ireland and can be seen in Figure 5.5. This record is less comparable with the record from Ireland, which is what would be

expected, due to the study site locations and the larger number of records available. It does however display the characteristic positive trend exhibited in the Irish, UK and European records, increasing from approx. 16,000BP to the present day. There is one decrease which is marked in both records and occurs at 8750BP. There are two major decreases in the North American record which occur earlier at 16,250BP and 14,250BP. These could be compared to two more extreme dips in the Irish record which occur slightly later at 15,250BP and 13,250BP. It is clear to see from the comparison of these two records that the record becomes smoother with the addition of a larger number of study sites, therefore the precision of the record from Ireland could be improved if additional data were available.

Irish and Global composite charcoal comparison

Finally a composite record was created using the Global Charcoal Database that included all the charcoal records from 390 lake sites spread throughout the globe. This record is compared to the record from Ireland and can be seen presented in Figure 5.6. It is clear looking at the global record that it is markedly similar to the North American composite record from Figure 5.5. The worldwide record is again much smoother than the Irish record and is a reflection of the larger set of data included in the transformation and synthesis. There are however a number of features which stand out as comparable from both records. Similar to the North American record, there are two decreases in the worldwide record at 16,250BP and 14,250BP, which correlate with slightly later decreases in the Irish record at 15,250BP and 13,250BP. There are also a number of small increases in the global record which are reflected by more extreme

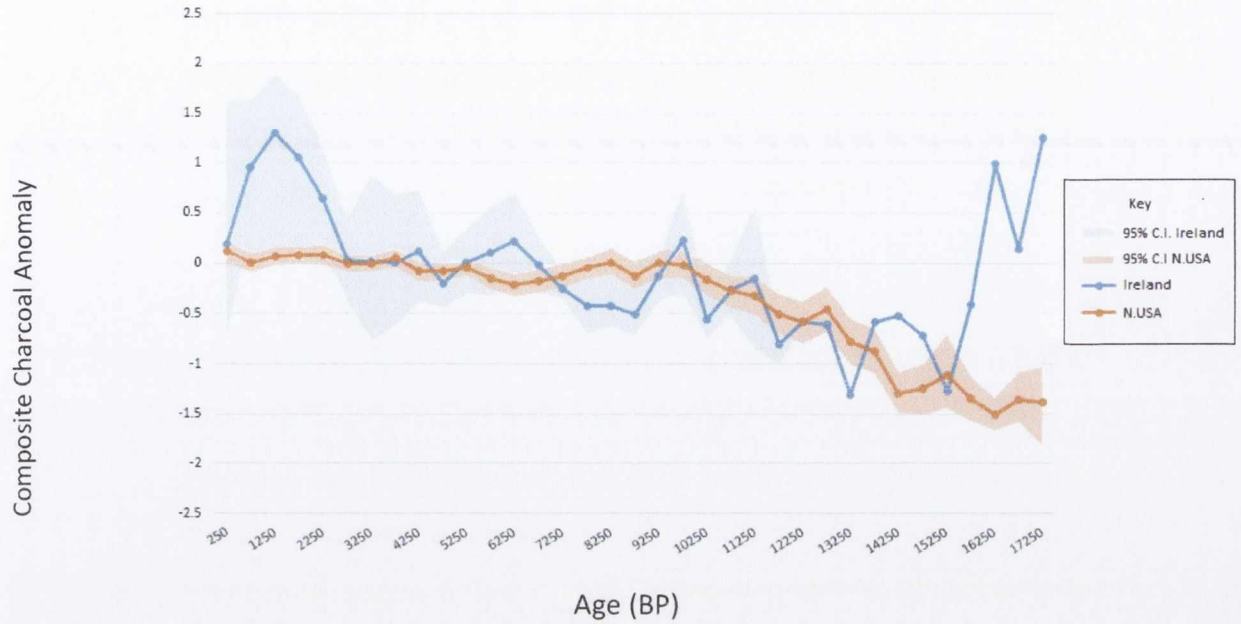


Figure 5.5 Comparison of composite charcoal records from Ireland and the Northern USA.

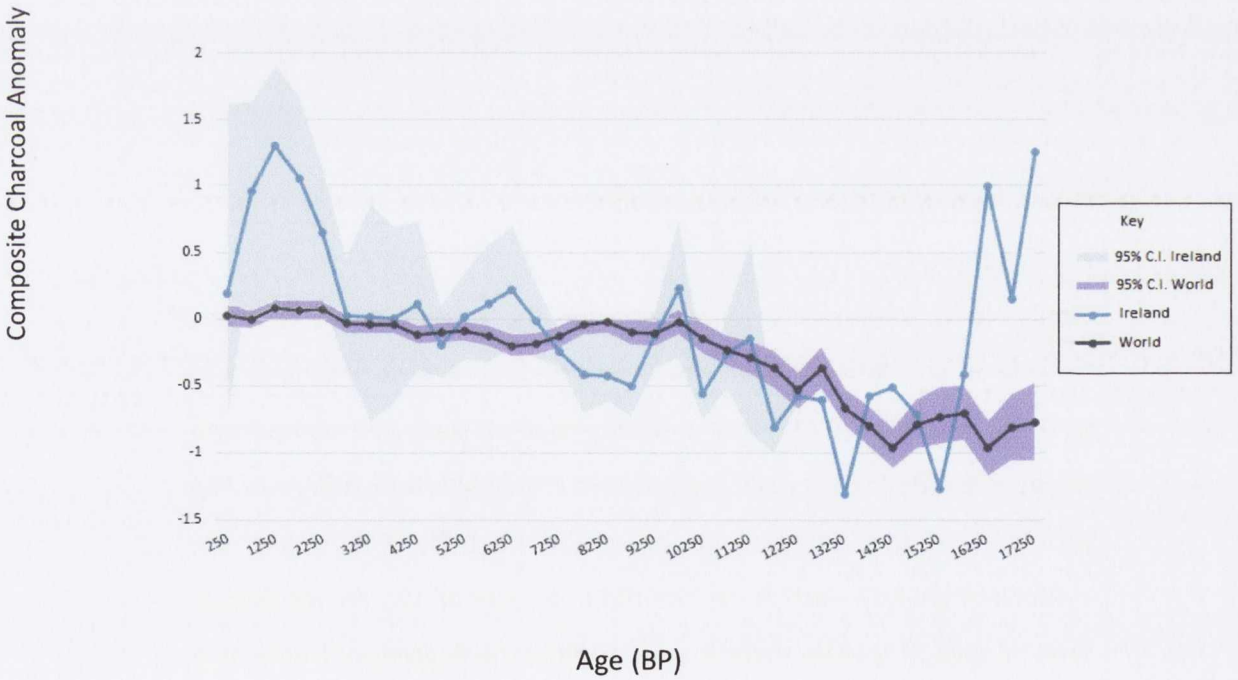


Figure 5.6 Comparison of composite charcoal records from Ireland and Worldwide.

increases in the Irish record, these occur at 12,750BP and 9750BP. It is clear from these records that there are a number of trends exhibited throughout the various records which may be the result of a common or series of common forcing factors, contributing to similar increases or decreases in fire frequency.

5.5.5 Kruskal Wallis Test

The Kruskal-Wallis test in R was applied to the individual charcoal records from each study site, to examine the relationship between the different archaeological periods outlined in Table 5.1. The results from these analyses are presented below, along with the results from the kruskalmc test which determines which relationships are significant. The critical p-value used here is 0.05.

Kruskal-Wallis Study Site Analysis

Similar to the composite record analysis the Kruskal-Wallis test was performed on each individual study site, and all records produced a p-value of less than 0.05. This indicates that at least one comparison between the defined archaeological periods is significantly different. The results from this analysis are presented in Table 5.7. Unlike the composite analysis each study site did not cover all the archaeological time periods, therefore there is a variation in the degrees of freedom in Table 5.7.

Table 5.5 Kruskal Wallis results; testing the relationship between archaeological time periods at each study site.

Study Site	Chi-squared	Degrees of Freedom	p-value
Ballinderry	39.24	1	3.75e-10
Borheen	365.6	6	<2.2e-16
Cornaher	26.03	3	9.40e-06
Cuckoo	75.39	5	7.71e-15
Diheen	14.18	1	0.00017
Kellys	128.11	5	<2.2e-16
Sheheree	410.84	5	<2.2e-16

The records here were also further analysed using the kruskalmc test to determine which archaeological time periods differ significantly at each of the study sites. The results from this analysis are presented in Table 5.8. These records highlight more significant differences between the archaeological time periods than the composite analysis, however not all archaeological periods are covered at each site. At Ballinderry Lough only one comparison between time periods was analysed and produced a significantly different result i.e. between the Medieval and Modern periods. This is similar to Diheen Lough which produced an identical result. At Borheen Lough 21 comparisons were carried out, and the analysis was dominated by significantly different results. Similar archaeological periods included the Mesolithic and Neolithic, Bronze Age and Iron Age, Bronze Age and Medieval, Iron Age and Medieval, Iron Age and Modern and Medieval and Modern. The results from Cornaher Lough produced 3 statistically similar and 3 significantly different comparisons. All the differing results were associated with comparisons involving the Palaeolithic period, while similarity between the time periods was

reported for latter comparisons towards the Bronze Age. Cuckoo Lough and Sheheree Lough also show significant differences between comparisons in the Palaeolithic period, between the Mesolithic, Neolithic and Bronze Age. It is difficult to see a pattern throughout the rest of the comparisons at these sites. Cuckoo Lough contains slightly more comparisons which report similarity with 7, while Sheheree Lough reports 5 similar comparisons between archaeological periods. The record from Kelly's Lough also produced 5 similar comparisons, with the differences being spread throughout the rest of the comparisons with no distinct pattern.

Table 5.6 kruskalmc test results for the charcoal record at each study site with respect to time period.

	Ballinderry	Borheen	Cornaher	Cuckoo	Diheen	Kellys	Sheheree
Palaeolithic-Mesolithic	-	1	1	1	-	0	1
Palaeolithic-Neolithic	-	1	1	1	-	1	1
Palaeolithic-Bronze Age	-	1	1	1	-	0	1
Palaeolithic-Iron Age	-	1	-	0	-	0	0
Palaeolithic-Medieval	-	1	-	0	-	1	1
Palaeolithic-Modern	-	1	-	-	-	-	-
Mesolithic-Neolithic	-	0	0	1	-	1	0
Mesolithic-Bronze Age	-	1	0	0	-	1	0
Mesolithic-Iron Age	-	1	-	0	-	0	1
Mesolithic-Medieval	-	1	-	1	-	1	1
Mesolithic-Modern	-	1	-	-	-	-	-
Neolithic-Bronze Age	-	1	0	0	-	0	0
Neolithic-Iron Age	-	1	-	0	-	1	1
Neolithic-Medieval	-	1	-	1	-	1	1
Neolithic-Modern	-	1	-	-	-	-	-
Bronze Age- Iron Age	-	0	-	0	-	1	1
Bronze Age- Medieval	-	0	-	1	-	1	1
Bronze Age-Modern	-	1	-	-	-	-	-
Iron Age-Medieval	-	0	-	1	-	1	0
Iron Age-Modern	-	0	-	-	-	-	-
Medieval-Modern	1	0	-	-	1	-	-

0-statistically similar 1-significantly different --time period not covered.

5.5.6 K-S Test Charcoal Synthesis

The two sample Kolmogorov-Smirnov Test was used to analyse whether two of the composite records are statistically similar. As part of the composite analysis the records were transformed, and interpolated to a constant time interval making them more comparable. Two composite

charcoal distributions were deemed significantly different from one another if $p<0.05$. The results from this analysis are presented below.

Ireland and UK K-S Test

The K-S test between the Irish and UK composite record produced a test statistic of D=0.1754 and a p-value of 0.6323. This indicates that the null hypothesis cannot be rejected, the two records are statistically similar at a significance level of 0.05.

Ireland and Europe K-S Test

Comparing the composite records from Ireland and Europe using a K-S test, a test statistic of D=0.2857 and a p-value =0.1151 were produced. This indicates that the records here are similar and the null hypothesis should be accepted.

Ireland and North America K-S Test

A test statistic D=0.3143 and a p-value of 0.06255 were produced in a comparison between Irish and North American composite charcoal data. The p-value is just above the significance level of 0.05 indicating that the null hypothesis should be accepted i.e. the two records are statistically similar.

Ireland and Global K-S Test

Finally using a K-S test to compare the composite record from Ireland to a composite record for lake sites across the globe, a value of D=0.3429 and p-value=0.03194 were produced. The p-value here is below the significance level of 0.05 indicating that the null hypothesis should be rejected, and the records are not statistically similar.

5.6 Discussion

Globally wildfire has been increasing throughout the Holocene (Marlon, 2013) and has close links to patterns of climate change (Aldersley et al., 2011) and human activity (Whitlock et al., 2010). Fire is controlled by a number of important factors, which are common at the regional, national and global scale; therefore it may be possible that similar general trends in wildfire exist at each of these scales at a range of locations across the globe. This chapter compares the specific fire regimes at a number of sites within Ireland to try and identify any common trends. A synthesis of the Irish fire record is also utilised to compare the record from Ireland to records from the UK, Europe, North America and the World.

The occurrence of fire events was compared between each of the study sites and a number of common trends were identified. Between the present day and 2000BP at Ballinderry, Borheen, Diheen and Kelly's Lough there are a number of fire events which coincide. The closest comparison can be made between Ballinderry and Borheen Lough where there are two events occurring at 103BP and 95BP respectively. Ballinderry and Diheen Lough also display a number of similar trends with two sets of events occurring approx. 20 years apart. A trend here can be seen between the upland sites of Borheen, Diheen and Kelly's Lough, with a similar altitude, vegetation and biodiversity they appear to display a number of fire events occurring at similar time periods. A significant comparison can also be made with Ballinderry Lough where the events occur slightly later than at the upland sites suggesting a delayed response to drivers of fire in the lowlands. This is in line with a study in the eastern Harz, Germany, which suggested that fire events were impacted by human activity but later at higher altitudes than in the lowlands (Robin et al., 2014).

From 2000BP to the start of the Holocene it is more difficult to identify any synchronous fire events between the study sites with a gap of less than 100 years. The closest events identified here are between Cornaher and Sheheree Lough and occur at 9751BP and 9752BP respectively. These two sites are in the lowlands at a similar altitude and have a similar vegetation composition. This analysis appears to show that the synchroniety of events is increasing towards the present day and it can be hypothesised that an overall influencing factor such as climate or human activity is having an increasingly regional effect towards the present day. This is similar to a study across various site in the Mediterranean which found a greater synchroniety of events from 4500BP to the present day (Vannière et al., 2011).

To identify any similar trends in charcoal concentration between the study sites and the various archaeological time periods a K-S test was carried out in R. There are three comparisons which are significantly similar; Borheen and Cuckoo Lough are similar in both the Bronze Age and Iron Age periods. Both these sites are located in an upland environment and have similar vegetation compositions suggesting that they would respond to drivers of fire in a similar way. The third comparison is between Borheen and Diheen Lough in the post Medieval to Modern period; these sites are both located within the Galty Mountains. All of these significant comparisons are between 4400BP and the present day supporting the idea of increased synchroniety in the later Holocene, possibly due to increased human activity This is also supported by a similar study in northwest Europe which identified a period of major fires occurring across a number of sites at approx. 2500BP (Cui et al., 2014).

The fire return intervals during each archaeological period were examined using a Weibull likelihood ratio test in an attempt to identify any significant correlations. During the Medieval and Modern time periods, 1600BP to the present day, three comparisons produced a p-

value >0.05 indicating that there is a relationship between the distribution of fire return intervals. These comparisons were between Ballinderry Lough with Borheen and Diheen Lough. The concentration of significant results in the later Holocene is not surprising as the distribution of fire return intervals is related to the occurrence of fire events, which were identified as synchronous in the later Holocene. A number of studies have also identified an increase in fire activity in the Late Holocene (Robin et al., 2014, Molinari et al., 2013), controlled by humans, climate and vegetation, with evidence of synchronous responses at a regional scale (Tinner et al., 2005). A similar analysis comparing the fire return intervals across the entire Holocene and each of the study sites produced 13 significant results out of 21 comparisons. The largest p-value occurs between Sheheree and Cuckoo Lough, which are both located in Killarney National Park. One comparison is significant between the upland sites, with a p-value of 0.228 between Borheen and Kelly's Lough. Two adjacent sites Ballinderry and Cornaher Lough also produce a significant result with a p-value of 0.328. This suggests that location and study site characteristics are important in influencing the nature of fire regimes, but due to the other significant variations it is not enough to characterise a definitive pattern. At smaller spatial scales variation in fire occurrence can be explained by factors such as location of ignition, fuel load, flammability, topography and specific weather conditions (Gavin et al., 2006, Rollins et al., 2002).

The magnitude of fire events was also compared using the Weibull likelihood ratio test, across archaeological periods and study sites. The Medieval period was identified as the most active in terms of fire events, with 17 in total, spread across Ballinderry, Borheen and Diheen Lough. This period coincides with the 'Medieval Warm Period' which is characterised by a period of increased temperature (Goosse et al., 2006, Calder et al., 2015). Cui et al. (2014) also reported an increase in fire activity from 2.5ka due to climate forcing and anthropogenic land-use,

which is in agreement with the overall fire history of north-western Europe.One comparison between these sites produced a p-value of 0.942 indicating that in terms of fire magnitude Ballinderry and Borheen Lough are similar. This may indicate that a similar vegetation composition occurred at these sites during this time and therefore similar fuels were being burnt to produce fires of a similar magnitude. Tinner et al. (2005) also carried out a study in the Alps which highlighted a synchronous fire response to similar vegetation composition across a number of sites. Looking at the records for the entire Holocene, 21 comparisons between fire magnitudes at each study site were carried out and of these 15 returned significant results. A number of trends can be identified; comparisons between the upland sites, Borheen, Diheen and Kelly's Lough, all produce significant results. As do adjacent sites in the lowlands, Ballinderry and Cornaher Lough, and Cuckoo and Sheheree Lough. This indicates that fires occurring in the same region are likely to have a similar magnitude. The magnitude of fires are controlled by a number of factors including vegetation type, moisture content, fuel load and overall meteorological conditions (Pyne et al., 1996).

A charcoal synthesis of the records from Ireland was carried out using the new 'Paleofire' package in R. This software provides a database and platform to create composite charcoal records and carry out comparisons between a wide variety of geographical areas (Blarquez et al., 2014). The records from Ireland were uploaded and manipulated in a comparison with lacustrine charcoal records from the UK, Europe, Northern USA and the entire world. The general trend across all of the sites is that fire was low in the early Holocene from approx. 15,000BP, and increases steadily towards the present day with numerous oscillations which are assumed to be attributed to variations in influencing factors such as human activity or climate. A study by Molinari et al. (2013) into Holocene wildfire in Europe, also confirms that fires are

higher in the later Holocene with significant controls being temperature and anthropogenic land-use change.

Looking at the composite records from the UK and Ireland there are a number of common trends which can be identified, and overall the records are correlated well. There is a significant decrease in charcoal activity at 13,250BP in both records, after which there is a sharp rise in fire activity. This is similar to a record from the Rhone Valley in France which identifies a period of low fire activity at approx. 12,600BP due to limited biomass and lower temperature, followed by a period of increased fire activity from 12,200BP (Doyen et al., 2015).

There is a marked peak in charcoal at 11,250BP in the UK, Irish and European record. This ties in with an increase in regional fire activity identified within the Northern Apennines, Italy at 11,500BP (Vescovi et al., 2010) and is consistent with a spike in the European temperature anomaly trend at approx. 11,200BP (Davis et al., 2003).

The records from Europe, North America and Worldwide display a smoother trend but all follow a similar general trend in charcoal. There are noticeable commonalities where fire activity peaks at 9750BP, 11250BP and 12750BP in all regions. Mauri et al. (2015) demonstrate a decrease in precipitation in Europe during the Early Holocene from 12ka to 11ka, which may help to explain the widespread peaks in fire activity at this time. Marlon et al., (2013) also found that there is an increase in biomass burning at approx. 10,000BP coinciding with a rapid rise in July temperatures (Viau and Gajewski, 2009). There is a marked decrease in fire activity in all areas except Ireland at 14250BP, with the Irish record decreasing slightly later at 14750BP. Another lull in activity occurs around 4750BP at all sites before generally increasing towards the present day.

There are instances where decreases appear to be delayed; at 16250BP and 14250BP there is a dip in the North America and Worldwide record,

which is picked up slightly later in the other records at 15250BP and 13250BP respectively. It should be noted here that as the region of study gets larger, there more charcoal records available to be manipulated via the 'paleofire' package, producing a smoother curve for the Worldwide composite record, and hence why the record appears smoother in the Later Holocene. Although the level of accuracy could be improved for Ireland it is still displaying significant trends which are correlated with all comparisons and especially the UK record.

It is clear from this analysis that fire can be related to a number of factors at regional and global scales, including temperature, precipitation and oscillation in atmospheric CO_2. Increases in CO_2 promote an increase in vegetation production which could increase fuel loads, leading to more frequent and intense wildfires (Calvo et al., 2014).

A Kruskal Wallis test was carried out between the different study sites to identify if any archaeological periods are significantly different. The Kruskal-Wallis analysis produced a p-value of less than 0.05 for each study site, indicating that at least one time period is significantly different at each site. The comparisons here are dominated by significantly different results, with a few trends existing between similar time periods. At Borheen Lough from the Iron Age to the present day all comparisons are similar, except between the Bronze Age and Modern periods. This suggests that the pattern of fire is more unified towards the present day at this site. Similarly at Cornaher Lough there is a distinct period of correlation between the Mesolithic, Neolithic and Bronze Age period; suggesting that fire activity was similar at this site during this time period. It is difficult to see a unified pattern here between study sites or geographical regions, this may suggest that individual site characteristics were not the dominant control for fire here. The Neolithic and Bronze Age proved similar across the most sites, at Cornaher, Cuckoo, Kelly's and Sheheree. The Mesolithic and Neolithic and Mesolithic and Bronze Age comparisons were all similar across three of the same sites. This may

indicate that fire was affecting these sites in the same way across these time periods.

Finally the composite record from Ireland was compared to the records from the UK, Europe, North America and Worldwide using a K-S test, to determine if the records are statistically similar. Most comparisons produced a p-value greater than 0.05 indicating that the Irish record is similar to the fire record from each of these other regions. The only comparison that was not significant was comparing Ireland with the Worldwide record. This is most likely due to the difference in resolution of sampling, as the Worldwide record has a smoother curve due to a higher number of study sites. The comparison is just below the critical value of 0.05 with a p-value of 0.32. These results would largely suggest that global factors such as climate change and increased human activity are having a mass impact in the occurrence and pattern of wildfire on an international scale.

These analyses have highlighted a number of regional trends in Ireland between the upland sites of Borheen, Diheen and Kelly's Lough, the sites within Killarney National Park; Cuckoo and Sheheree Lough, and the sites within the Irish Midlands; Ballinderry and Cornaher Lough. However data analysis also highlights the general independence of these sites, displaying more unique features and trends than common characteristics. This would suggest that individual site conditions such as topography, soil type, vegetation and meteorological conditions are influencing fire occurrence. On a larger scale when looking at the composite record for Ireland in comparison with the UK, Europe, North America and the World, it is apparent that the records display many similar trends, which are backed up by further statistical tests. This suggests that global drivers of wildfire such as climate change are having a common influence within Ireland at a national scale.

5.7 Conclusion

This chapter presents a detailed investigation into the trends in wildfire across seven study sites throughout Ireland, and examines the possible drivers of these trends at a variety of geographical scales, and how they correlate with composite trends in wildfire from the UK, Europe, North America and the World. From the numerous statistical analyses presented a number of conclusions can be drawn;

1. A number of fire events are synchronous on a regional scale, with respect to upland and lowland ecosystems within Ireland.
2. The composite record of fire from Ireland follows similar trends in fire from the UK, Europe, North America and the World.
3. The Medieval period stands out as a period of increased fire activity within Ireland.
4. Increases or decrease in fire activity on a large scale can be correlated with changes in climate such as temperature, precipitation and CO_2 apparent in surrounding literature
5. On a smaller scale individual site conditions such as topography, soil type, vegetation and meteorological conditions influence fire occurrence.
6. The Late Holocene and Late Palaeolithic are characterised by increased levels of fire due to increased temperature and increased biomass.
7. Irish sites largely display independent fire regimes at a local scale, however the composite record highlights how the general trend for Ireland is in agreement with trends in wildfire from across the globe.

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Chapter 6

Examining the relationship between fire and vegetation throughout the Holocene in Ireland

Abstract

Wildfires have been occurring throughout the Holocene and are part of the natural environment, acting as an agent of renewal and change within an ecosystem. Ireland has been no exception in its exposure to wildfire, however its effect on the landscape and vegetation has remained largely undocumented. This chapter examines the interaction between fire and vegetation throughout the Holocene at seven study sites spread throughout Ireland; in an attempt to identify any fire tolerant or fire prone species which may exist. This analysis will also quantify the level of impact of identified fire events and allow for future recommendations in light of the knowledge gained. As fire frequency and intensity is predicted to increase globally in the future and has been observed to increase in Ireland in recent years; studies such as this are key to the understanding of fire ecology which has remained largely unstudied within the Irish landscape. Results show that identified fire events are associated with periods of instability and change, and generally occur within similar time periods or under similar vegetation and climate conditions. The fire vegetation analysis has also identified a number of specific species as fire adapted (*Quercus, Pinus* and Poaceae), fire dependent (*Corylus, Alnus, Pinus* and *Salix*), fire resistant (*Betula, Quercus, Pinus*, Poaceae and *Calluna*) and fire sensitive (*Ulmus*).

6.1 Introduction

The study of environmental change throughout the Holocene is extremely important in understanding current changes to our environment and ecosystems (Froyd and Willis, 2008). It allows us to reconstruct the character of the past landscapes, past climatic conditions, catchment processes and identify extreme events that may have occurred in the surrounding landscape (Smol, 2010). These reconstructions are possible through multi-proxy studies which utilise pollen grains, charcoal fragments, plant macrofossils and diatoms to name but a few, which have built up in lake and peat sediments over time, providing a chronological record of past environmental change (Birks and Birks, 2006).

This study looks at the record from the Late-glacial and throughout the Holocene, covering a time period of 18,000 years. Marine Isotope stage 2 (22-12,000BP) was an extremely complex cold period which exhibited expansions and contractions of ice sheets, in conjunction with a sequence of climatic oscillations (Coxon, 2001). However by 13,000BP most of Ireland was free of ice and evidence of plants species can be seen in Late Glacial and Early Holocene records. The Holocene began with a dramatic rise in temperature (approx. 12,000), which transformed the climate in Ireland from tundra to temperate within the space of a decade (Haslett et al., 2006). The postglacial colonisation of the Irish landscape is well known and represented in numerous Irish pollen diagrams e.g. Clara Bog (Connolly, 1999), where the treeless tundra landscape sees the establishment of more thermophilious taxa. The beginning of the Holocene is characterised by the rapid and widespread expansion of *Juniperus*, which was followed by *Betula* a pioneer tree. The subsequent arrival of *Corylus* lead to the decline in *Betula* and continued decline in *Juniperus* over approx. 500 years, and is evident in all early Holocene

pollen records (Mitchell, 1995). The arrival of other principal tree taxa can be seen from approx. 10,000BP, and includes *Pinus, Ulmus*, and *Quercus*. These species spread rapidly throughout Ireland with their range extending across the majority of the country by approx. 8500BP (Berglund et al., 1996).

Ireland has an extensive coverage of pollen diagrams which has facilitated a number of general conclusions about spatial trends in vegetation coverage throughout the Holocene (Bennett and Willis, 2001, Mitchell and Ryan, 1997, Mitchell, 1996). The Irish Midlands atop base-rich soils supported forests dominated by *Ulmus, Quercus* and *Corylus*. The more acidic soils to the North, East and South are dominated by *Quercus* woodland, with the poorer soils of the West and Uplands supporting *Pinus* dominated populations. Pollen diagrams also provide detailed records on a local scale which may highlight site specific variations. Specifically this chapter uses the palynological record to reconstruct the vegetation composition from the Late Glacial and Early Holocene to the present day at seven study sites. It also uses charcoal fragments to infer past fire regimes, specific fire events and their magnitude to assess their impact on the surrounding vegetation. These analyses will enable the identification of fire prone or fire resilient taxa, and identify how vegetation changes before and after a fire event, helping to predict the future impacts of wildfire.

The study of wildfire and its effect on vegetation is an ever expanding area of research. It can be divided into a wide range of topics including the effect of fire on specific species such as *Betula* (Reyes et al., 1997) or *Quercus* (Cocking et al., 2014). How fire effects specific vegetation types such as trees (Dickinson and Johnson, 2001) or grasslands (Cheney and Gould, 1995), and how effectively and quickly they can regenerate (Casady et al., 2010). How it impacts vegetation communities altering their structure, composition and characteristics. Fire is also seen to have positive impacts for vegetation and ecosystems; providing new habitats,

encouraging new plant generations to colonise, killing disease, and renewing soil geochemistry (Morton et al., 2003). It is therefore important to carry out studies such as this to examine the positive and negative impacts of fire, especially in lesser studied areas such as Ireland, as fires are predicted to increase in the future in conjunction with climate change (Marlon et al., 2013).When studying the impact of fire on plant communities or individual species, it is important to understand the condition of the plant prior to fire occurrence; as other disturbances such as drought, disease or overgrazing can increase the impact of wildfire (Dale et al., 2001). Tree and shrub taxa also vary within and between species in their response to fire, and this response is dependent on a number of factors related to the fire such as intensity, fire return interval and severity. Surrounding climate conditions, weather, slope, aspect and soil characteristics should also not be underestimated in their contribution to the ignition and spread of wildfire (Parisien and Moritz, 2009). Factors related to the individual species are also important such as moisture content, fuel loading and stem or bark characteristics. It is not difficult to see the challenge that has arisen in relation to the management of wildfire, due to the complex network of interrelated and influencing factors which can be specific not only to a geographical area but also to vegetation type and species (Gill and Stephens, 2009).

Fire management and sustainability are therefore contentious issues which have evolved with differing opinions in recent decades, and have more recently displayed a shift from a fire suppression approach to a prescribed fire and management approach (Fernandes and Botelho, 2003). A variety of management techniques have been adopted in recent years which have utilised the knowledge from a variety of analytical studies. The most controversial management technique is the use of prescribed burning which is applied in areas where there is an excessive accumulation of fuel or where there has been a prolonged fire return interval or period of fire suppression and poor management (Lázaro,

2010). Careful consideration is needed before carrying out any type of burning and national guidelines must be followed to ensure appropriate practice (Davies et al., 2008). Another useful form of management is the use of a firebreak, which is a gap in the flammable or fire prone vegetation slowing or stopping the spread of wildfire. Fire breaks can occur naturally and are effective in helping to reduce the size and impact of wildfires (Edwards et al., 2008). Another approach has been to plant 'fire adapted' species which have evolved with special traits providing them with the ability to survive fires at various stages in their life cycles. These traits include serotinous cones, fire resistant bark, fire resistant foliage, or rapid growth and development post fire, and enable various kinds of plants to survive and thrive in a fire prone environment (Kozlowski, 2012). Such species may not always be appropriate in each geographical location therefore it is important to develop a specific fire management code of practice for each region in light of national guidelines and fire ecology research.

There has been little research carried out in Ireland on the role and impacts of fire within the Irish landscape, especially in a palaeoecological context. The only potential record of fire activity that exists is where microscopic charcoal has been quantified on pollen slides and represented in published pollen diagrams. However this practice was not universal and records are sporadic. Microscopic charcoal also represents a more widespread fire activity within the surrounding landscape and is therefore not accurate in estimating local fire events.

A number of previous studies have highlighted that fire may have had a role in the development of blanket bog formation (Murphy, 2008, Moore, 1993, Mallik, 1983). Mallik (1983) showed that the addition of charcoal to a soil following a heathland fire alters its drainage properties i.e. the fine, inert particles of carbon reduce the porosity of the soil. It is also possible than the landscape was cleared of trees via burning practices which helped to initiate peatland development (Moore 1993).

A more recent study carried out across Europe highlights the more recent impact of fire on peatland hydrology (Marcisz et al., 2014). It has also been widely accepted that humans have been using fire in a variety of ways throughout the later Holocene, having significant and altering impacts on the surrounding landscape. A recent study was carried out in Ireland to illustrate the use of fire at a number of archaeological sites and the impact this had on adjacent woodland (O'Carroll 2012). It is clear that both natural and anthropogenic fire has been impacting the Irish landscape throughout the Holocene, however there has been no previous attempt to quantify the impact across a range of sites from varying ecosystems.

This study therefore focuses on the vegetation dynamics at a number of locations throughout Ireland and attempts to reconstruct the impacts that specific fire events have at each site. The records extend from the beginning of the Holocene to the present day and provide an extensive record of fire and vegetation history within Ireland. A key aim is to identify the relationship fire has with specific species indigenous to Ireland to identify if any fire adapted or fire prone species exist, in the hope this knowledge will inform future management practices.

6.2 Aims

1. Identify the impact of wildfire on the surrounding landscape and vegetation at each of the specific study sites.

2. Identify any significant relationships between the charcoal record and specific taxa.

3. Demonstrate how specific taxa can change before and after a fire event.

4. Deduce specific taxa that are vulnerable or resilient to fire in order to anticipate future fire effects.

6.3 Study Sites

All seven study sites (discussed in detail in Chapter 3) are included in this analysis examining the interaction between fire and vegetation. The macroscopic charcoal data presented here were measured as part of this study, except for at Kelly's Lough (Murphy, 2008) and Ballinderry Lough (Brooks, 2009) where the data were generated as part of previous Masters' theses using similar techniques. The pollen and vegetation data for each of the study sites were generated as part of a variety of studies carried out at Trinity College Dublin (details are outlined in Table 2.1, Chapter 2) however the pollen data for Cuckoo Lough was generated as part of this thesis. Pollen diagrams have been standardised and redrawn in Tilia (Grimm, 1993), with up to date chronologies created using BChron (Haslett and Parnell, 2008), to aid an accurate comparison between study sites.

6.4 Methodology

To generate the macro-charcoal data presented, charcoal analysis was carried out on the sediment cores from selected sites and the method for preparation is adapted from those described by Mooney and Black (2003) and Mooney and Radford (2001). Digital image analysis using Image J was applied once the samples were prepared, to generate count and area data, and follows methods similar to Schlachter (2012). Microscopic charcoal records are available for all sites except Ballinderry Lough, and are represented on the pollen diagrams within this chapter. The microscopic charcoal was estimated using the point count method proposed by Clark (1983), using the slides which were prepared for pollen analysis to produce an estimate of charcoal concentration, and was carried out as part of previous projects at Trinity College Dublin. The

microscopic charcoal at Cuckoo Lough was counted on the pollen slides to produce a charcoal count, which was scaled to estimate concentration using the Lycopodium tablets. Each of the sediment cores was also radiocarbon dated, and a chronology was produced using BChron and Intcal13 calibration curve (Haslett and Parnell, 2008). Dates are discussed as BP in this chapter representing cal.BP. The vegetation composition at each site was determined via standard pollen analysis using methods adapted from Shackley (1981) and is outlined in Paleoethnobotany: A handbook of Procedures (Pearsall, 1989). The pollen from Cuckoo Lough was prepared in conjunction with this thesis, the remaining pollen is available from previous studies (Table 2.1 Chapter 2). The pollen was counted and identified using the reference collection at Trinity College Dublin. Pollen and spore nomenclature follows. The pollen sum was calculated and includes all identified pollen and spore taxa, but excludes aquatics. A microscopic analysis of macrofossils was also carried out at each pollen depth (Mauquoy, 2011) at Cuckoo Lough. Loss on ignition analysis was also carried out here on each cm of the core, to reveal any variation between organic and inorganic material found in the sediment. Loss on ignition data were also available from previous analyses at Cornaher, Ballinderry and Kelly's Lough. The data are based on differential thermal analysis i.e. the sample is weighed before and after ignition and the weight loss percentage determined by difference (Dean, 1974).

6.4.1 Pollen Diagram

A pollen diagram representing the vegetation composition at each study site was produced in Tilia 2.0.36 (Grimm, 1993). Each diagram is interpreted in relation to the vegetation and charcoal transition over time, to visually identify any significant changes in composition perhaps in response to increased charcoal. It is also possible to identify significant

changes within the wider landscape in response to climate events, disease or extreme events e.g. transition from grassland to woodland or evidence of *Pinus* (pine) and *Ulmus* (elm) decline. Macroscopic and Microscopic charcoal concentration curves are represented to the left of the diagram with loss on ignition and pollen sums on the right.

6.4.2 Spearman's Correlation

To examine the relationship between fire and selected taxa, a Spearman's correlation was carried out in R between pollen percentages (%) of *Pinus* (pine), *Quercus* (oak), *Alnus* (alder), *Calluna* (heather), *Sphagnum* (peat moss), Poaceae (grass), *Pteridium* (bracken), *Plantago* (plantains), *Corylus* (hazel) and the percentage of all trees and shrubs, with the charcoal concentration at corresponding pollen depths. A similar correlation analysis was also carried out between each of these taxa and the charcoal concentration, being calculated as a moving 3 point average as charcoal and pollen were sampled at varying resolutions. The taxa examined here were chosen due to their dominance in most pollen records and the most likely to show a relationship with the identified charcoal concentration. The correlation highlights if a relationship exists between the two variables, and the significance of these correlations was tested at three probability levels ($P<0.001$, $P<0.01$ and $P<0.05$) using a two tailed t-test. Correlation matrices were also drawn in R using the PerformanceAnalytics package (Carl et al., 2009) to graphically display selected results from each site.

6.4.3 Rate of Change Analysis

The rate of change (ROC) between adjacent pollen samples was quantified by the squared chord distance (Grimm and Jacobson Jr, 1992)

for each of the study sites. The chronologies from each site were then used to scale ROC to units per 100 years (Mitchell, 2013). The rate of change calculations were also then smoothed using a three point moving average to compensate for the inequality in the pollen sample resolution. The ROC and smoothed ROC were plotted for each site in conjunction with the identified fire events. The rate of change is a useful variable for identifying regionally synchronous palynological changes, and indicates major disturbance or change within the site catchment e.g. response to fire, climate change or human activity.

6.4.4 NMDS Ordination

Nonmetric Multidimensional Scaling ordination was used to plot the pollen data using a community dissimilarity matrix based on species composition, and is used to explore the relationship between pollen samples. In this analysis the Bray-Curtis index was used to compute the distance in the dissimilarity matrix. This was carried out using the Vegan and MASS packages in R (Oksanen et al., 2013, Ripley et al., 2014). A number of ordination plots were produced for each study site, representing an ordination for each individual pollen depth, an ordination reflecting archaeological periods and an ordination representing fire event occurrence. Pollen samples that have similar species composition will appear as points near each other whereas samples that have different species compositions will be further away from each other within the ordination space. To check for significant differences between archaeological periods and between fire events two sets of PERMANOVA's were carried out for each study site in R (Venables and Smith, 2005). The null hypotheses state that there is no significant difference between archaeological periods or fire events, and the significance level is p-value= 0.05.

6.4.5 Paired T-Test

To analyse whether certain taxa are potentially significantly impacted by fire, the vegetation composition before and after each fire event was compared using a paired t-test. The data from each study site were composited and compared in a 200 year time window in R under the null hypothesis of equality of averages. A 200 year time window was chosen based on the nature of the data and to ensure an adequate resolution for sampling. A number of selected taxa were examined; *Pinus, Quercus, Alnus, Calluna, Sphagnum*, Poaceae, *Pteridium, Plantago, Corylus* and the percentage of all trees and shrubs. This analysis will highlight whether the taxa change significantly before and after each fire event across all of the study sites.

6.4.6 Multi Response Permutation Procedure (MRPP)

MRPP analysis was carried out using the vegan package in R (Oksanen et al., 2013) for each of the study sites, to test whether there is a significant difference between the vegetation between two or more of the archaeological time periods. MRPP utilises the Bray-Curtis index to calculate pairwise distances for the entire dataset, calculating the average distance within each group. The delta value is then calculated;

$$delta = \delta = \sum_{i=1}^{g} C_i x_i$$

for *g* groups, where *C* is a weight that depends on the number of items in the groups (normally $C_i = n_i / N$, where n_i is the number of items in group *i* and *N* is the total number of items).

Finally the probability of a similar delta value or smaller is calculated through Monte Carlo permutations.

6.5 Results

6.5.1 Pollen Analysis

The vegetation transitions are discussed at each study site in reference to identified fire events, and any increases and decreases in dominant species. Pollen diagrams are presented displaying pollen percentages, loss on ignition where available and charcoal concentration over time. The three fire events with the largest magnitude are represented on each diagram with a red line.

Irish Midlands

Ballinderry Lough

Ballinderry Lough is located near the border of Counties Offaly and Westmeath in the Irish Midlands. The lake lies at an elevation of 80m atop a bedrock of Carboniferous Limestone. The vegetation composition at this site was quantified through a palynological analysis and represented on the pollen diagram from Ballinderry Lough, Figure 6.1.1.. The diagram is divided into the seven archaeological time periods outlined previously. The Medieval period comprises a large proportion of the diagram and this is due to the multiple radiocarbon dates from this period and the resulting chronology produced. This may restrict the reliability of the interpretation from this site as there appears to be an uncharacteristically slow sedimentation rate during the Medieval period, with 4000 years from the Neolithic to Iron Age compressed into approx. 40cm at the bottom of the diagram. The diagram is dominated by tree species such as *Corylus* and *Alnus*, and herbaceous taxa such as Poaceae and Cyperaceae. The three largest fire events identified at this site are represented by red lines on the pollen diagram. The top most fire event appears to display the most impact and is followed by a significant

decrease in the dominant taxa *Corylus* and Cyperaceae decreasing by approx. 5% abundance, and is followed by a dramatic increase in taxa such as Poaceae and *Betula*, also increasing by approx. 5% abundance. The bottom two fire events also appear to be associated with decreases in the dominant taxa *Corylus* and *Calluna*, and followed by increases in herbaceous taxa such as Cyperaceae and in the case of the event at approx. 132cm also Poaceae. The largest amount of charcoal activity appears to be occurring within the latter half of the Medieval period which occupies the majority of the diagram. There are a number of other significant trends which can be seen within the diagram; there is a large decrease in *Corylus* at approx. 680BP. This coincides with an increase in *Calluna*, which may suggest woodland clearance being replaced by grasses. There is also a large decrease in loss on ignition at approx. 1240BP, however the vegetation at the same depth does not appear to be affected. Indicators of human activity such as *Plantago* and *Cerealia* are consistently present at low levels throughout the majority of the diagram. *Pinus* declines early in the diagram and remains low, recovering towards the Modern period. This pattern has been observed in most pollen profiles from Ireland to represent the *Pinus* decline which was thought to be extinct from most of Ireland by 1600BP (Bradshaw and Browne, 1987). There are dips in *Betula*, *Quercus* and *Alnus* during the Later Bronze Age and Early Iron Age period. These trees recover by the Later Iron Age coinciding with a reduction in Poaceae which is synchronous with the Later Iron Age lull (O'Carroll, 2012). Finally notable dips in tree taxa can be seen towards the top of the diagram which most likely represent clearance phases, with Poaceae and *Cerealia* also increasing significantly towards the present day. Further detail on the pollen and other aspects associated with this site can be found in O'Carroll (2012).

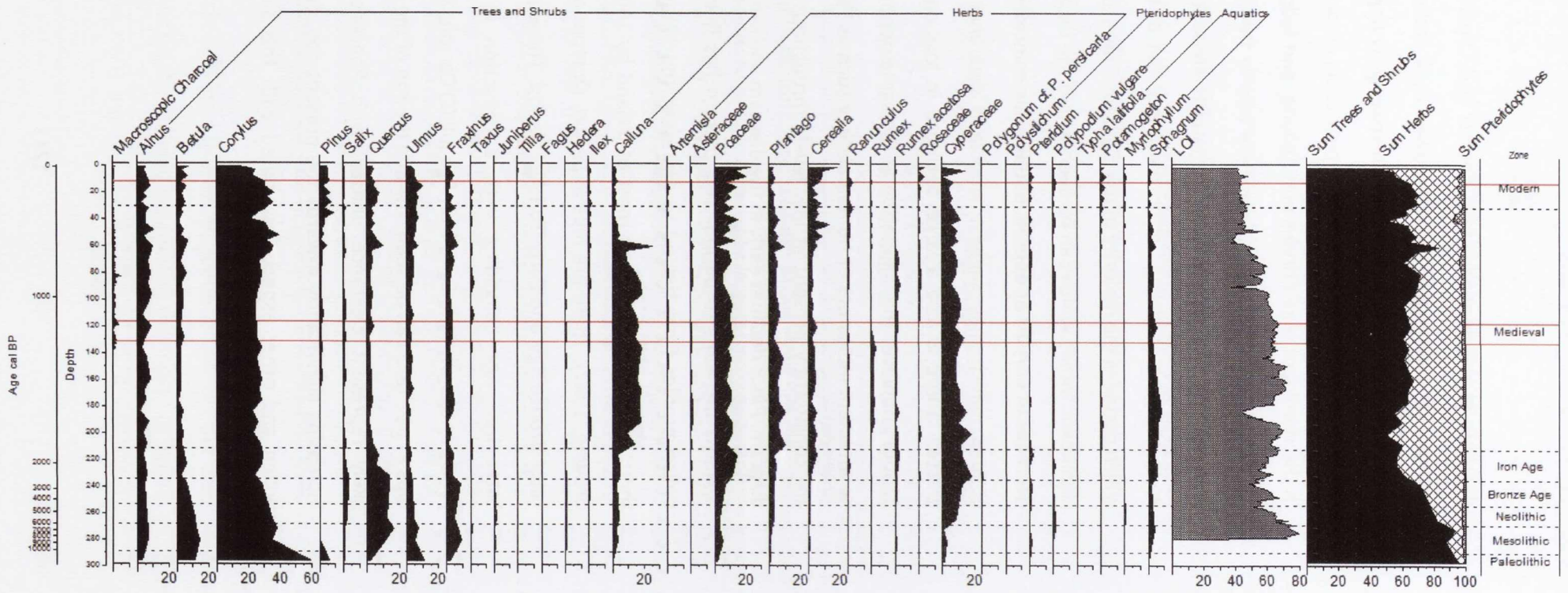


Figure 6.1.1 Pollen diagram from Ballinderry Lough, red lines represent three largest fire events, Macroscopic charcoal is represent in concentration (pieces cm^{-3}).

Cornaher Lough

Cornaher Lough is located approx. 9km to the east of Ballinderry Lough in County Westmeath. The lake covers an area of approx. 0.24ha at an elevation of 91m, and is relatively sheltered by a nearby esker, Long Hill esker. The vegetation transitions were investigated at Cornaher Lough and are represented on the pollen diagram, Figure 6.1.2 overleaf. The diagram covers the archaeological periods from the present day to the Palaeolithic. A steady sedimentation rate appears to be maintained for the majority of the diagram, however the period between 7000 and 9000BP appears to have experienced an increased sedimentation rate. It is clear from this diagram that there is a significant transition in the vegetation during the early Mesolithic at approx. 9750BP. This transition is synchronous with one of the largest fire events within the record represent by a red line on the diagram. The transition is characterised by a change in the dominant vegetation from *Betula, Salix, Juniperus* and Poaceae to a dominance in other tree taxa such as *Corylus, Alnus, Quercus* and *Ulmus* forming the main part of the woodland canopy. The remaining two fire events displayed in this diagram are followed by dips in vegetation such as *Quercus* and *Ulmus*, and increases in taxa such as *Corylus, Alnus* and *Rumex.* The topmost fire event also shows a marked reduced in *Fraxinus* follow the fire event. The majority of charcoal activity appears to be occurring in the Bronze Age and Mesolithic time periods at this site. The most recent fire event shown here at approx. 3750BP also follows a large peak in microscopic charcoal which indicates burning in the wider landscape. *Pinus* is present throughout the Palaeolithic and Mesolithic periods, and begins to experience declines during the Neolithic, completely disappearing by 4000BP; this represents the *Pinus* decline which can be seen at numerous sites throughout Ireland (Roche et al., 2009). There are further declines during the Neolithic in *Ulmus* at approx. 5000BP which represent the elm decline, a synchronous event throughout the UK and Ireland thought to be due to climate and

anthropogenic factors (Parker et al., 2002). Human indicators can be seen in significant numbers from the Bronze Age to the present day, represented by small oscillations in *Plantago* and *Cerealia* pollen. Another transition appears to occur moving into the Iron Age; Poaceae and Cyperaceae increase largely and tree species such as *Quercus, Ulmus* and *Fraxinus* continue to decrease almost disappearing towards the present day. This is indicative of increased anthropogenic activity, supported by an increase in *Cerealia* pollen which is evidence of cereal cultivation adjacent to the site. The Bronze Age period displays significant peaks in the abundance of *Sigmapolis* which may be in response to an increase in nutrient input into the lake, which is coupled with a rise in anthropogenic activity (Heery, 1998). The Later Iron Age lull is less apparent at this site in comparison with others from Ireland, but there is still a characteristic increase in arboreal pollen and loss on ignition. The Medieval period reflects a further increase in the expansion of agriculture in the midlands with a reduction in arboreal pollen and an increase in Poaceae, *Plantago, Rumex* and *Cerealia.* Further pollen detail and discussion for Cornaher Lough is available from Heery (1997).

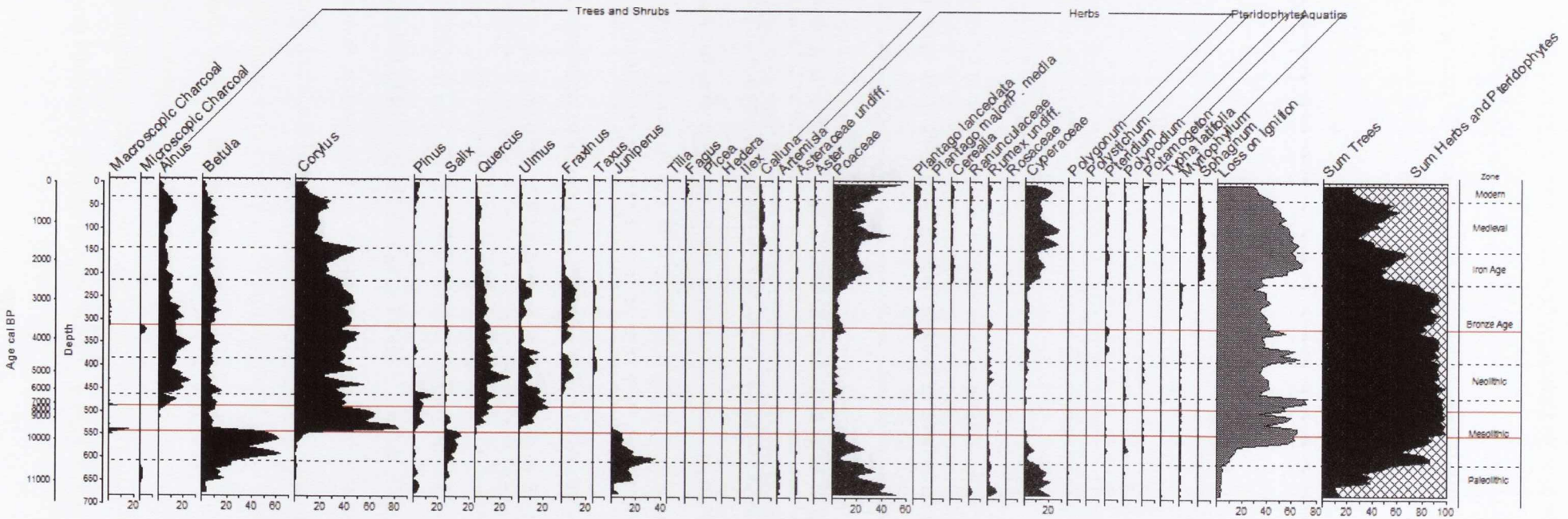


Figure 6.1.2 Pollen diagram from Cornaher Lough, red lines represent three largest fire events, Macroscopic and Microscopic charcoal are represented as concentration (pieces cm^{-3}).

Killarney National Park

Cuckoo Lough

Cuckoo Lough is a small circular lake located in the townland of Glena within Killarney National Park. It lies at an elevation of 32m atop a bedrock of Old Red Sandstone. The pollen diagram from Cuckoo Lough can be seen in Figure 6.1.3 it covers a range of archaeological time periods from the present day back to the Palaeolithic at the beginning of the Holocene. The pollen diagram is divided by each time period with the Mesolithic and Palaeolithic periods covering almost half of the diagram. Sedimentation appears steady throughout the record from approx. 15,000BP to 2000BP, but appears slower towards the present day where the last 2000 years cover approx. a quarter of the entire diagram. The dominant taxa represented here are the common tree species indigenous to Ireland; *Betula, Corylus, Pinus* and *Quercus,* with other significant taxa recorded here such as *Calluna*, Poaceae and *Sphagnum*. Only one identified fire event is covered by the pollen record at this site and is represented by a red line on the pollen diagram. This fire event is followed by increases in *Betula, Alnus* and *Corylus*, and followed by decreases in *Pinus* and Poaceae. Evidence of the *Pinus* decline can again be seen at this site where *Pinus* percentages begin to decrease at the beginning of the Bronze Age at approx. 4000BP, remaining significantly low towards the present day. Evidence of the *Ulmus* decline can also be seen in this diagram at approx. 5000BP where there is a notable lull in *Ulmus* percentages, before recovering again at approx. 3800BP. Human indicators within the diagram such as *Plantago,* Cyperaceae, *Rumex* and *Cerealia* are present in low levels throughout most of the graph, showing a marked increase in the Medieval and Modern periods towards the top of the diagram, indicating an increase agricultural activity. Charcoal activity here remains high in the Neolithic and Medieval periods, with a marked decrease during the Bronze Age, which coincides with increased loss on ignition and a slight expansion of tree species, especially *Quercus*.

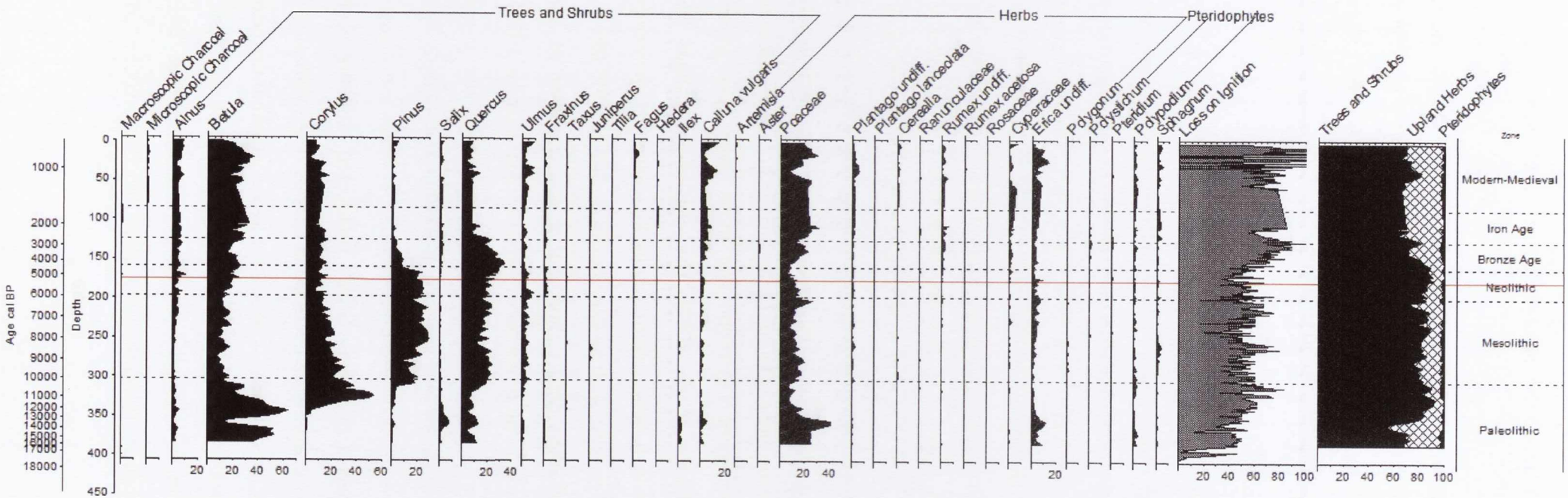


Figure 6.1.3 Pollen diagram from Cuckoo Lough, red line represents identified fire event, Macroscopic and Microscopic charcoal are represented as concentration (pieces cm^{-3}).

There is also some potential evidence here for the 8.2ka climate event, reflected here in the expansion of *Pinus* and a decrease in *Corylus* and *Quercus* at 258cm, where there is interpreted to be a shift to colder climatic conditions (Ghilardi and O'Connell, 2013).

Sheheree Lough

Sheheree Lough is also located within Killarney National Park, and lies approx. 4km east of Ross Island in the townland of Sheheree. This site is now bogland which replaced the former lake. This transition is presented in the pollen diagram post 3000BP with a marked increase in Poaceae, *Calluna,* Cyperaceae, and *Sphagnum*, coinciding with a decrease in *Alnus* and *Betula.* In contrast to Cuckoo Lough this site is underlain by Carboniferous Limestone. The pollen diagram from Sheheree Lough can be seen in Figure 6.1.4 and covers the entire Holocene from the present day back to the Palaeolithic. The bottom of the record represents the transition from the late glacial to the early Holocene, characterised by a shift in the dominant vegetation and move from open ground to woodland (Schwark et al., 2002). The vegetation changes from a dominance of taxa *Juniperus, Betula, Salix*, Poaceae and Cyperaceae to a dominance of tree taxa such as *Corylus, Pinus, Quercus* and *Ulmus.* The introduction of *Alnus* occurs shortly after this transition at approx. 9800BP indicating a shift to wetter climatic conditions (Lowe, 1993). The largest fire event at this site occurs at approx. 3800BP, with two other events occurring earlier in the record at 9750BP and 9950BP. The fire events here are characterised by a decrease in *Pinus* and *Alnus*, with herbaceous species remaining largely unaffected. The fire event at 9950BP is also followed by a decrease in Corylus. The event at 9750BP shows an initial increase with a significant decrease within the next 100 years. The dramatic spike in charcoal at approx. 3800BP coincides with the mining of copper ore by fire-setting at the adjacent Ross Island site which occurred during the early Bronze Age from 3900—400BP (O'Brien

and Brindley, 2004). The microscopic charcoal is more constant in this part of the diagram, and represents burning outside the lake catchment; its abundance suggests that more frequent fires may have been occurring in the wider landscape. There is a dramatic disappearance of *Pinus* at approx. 1800BP which is later than the commonly identified decline of *Pinus* at approx. 4400BP (Roche et al., 2009). Charcoal analysis from the nearby Ross Island copper mining site identifies that pine was used during the Early Bronze Age within the Killarney valley (O'Brien and Brindley, 2004). The reintroduction can also be seen clearly in the diagram at approx. 200BP where the percentage increase from 0 to over 20% abundance. The *Ulmus* decline is less pronounced at this site but declines slowly from approx. 5000BP remaining at less than 5% abundance for the rest of the record. Sheheree Lough has the strongest record of anthropogenic activity identified in this analysis. A period of significant woodland clearance can be seen in the last 1000 years of the pollen diagram where there is a significant drop in the dominant tree taxa. The low levels of cereal pollen indicate a dominance of pastoral activity with arable agriculture playing a lesser role. Another anthropogenic indicator, *Plantago* is recorded in high levels approaching 20% abundance towards the top of the diagram. There is a large increase in *Sphagnum* and *Pteridium* throughout the Medieval period then decreasing in the Modern period, where there is a recovery of woodland and decrease in agricultural activity from 100BP to the present day which coincides with rural depopulation following the Great famine.

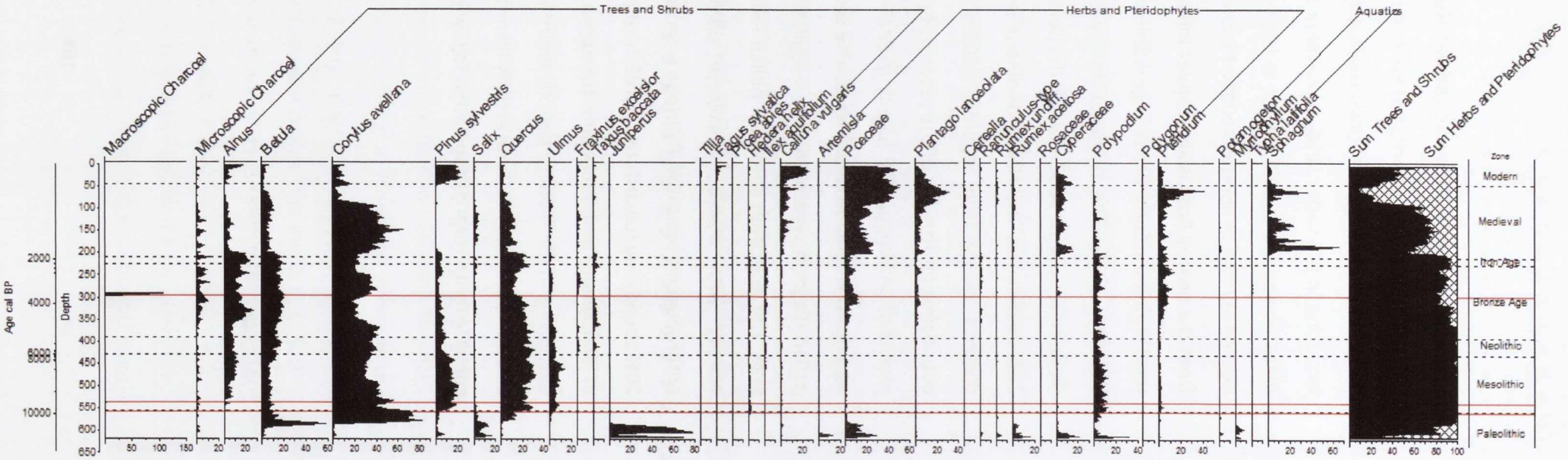


Figure 6.1.4 Pollen diagram from Sheheree Lough, red lines represent three largest fire events, Macroscopic and Microscopic charcoal are represented as concentration (pieces cm^{-3}).

Galty Mountains

Borheen Lough

Borheen Lough is a high altitude (476m) corrie lake located in the Galty Mountains. It covers an area of 2.45ha and is underlain by Old Red Sandstone. Figure 6.1.5 displays the pollen diagram from Borheen Lough, which covers each archaeological time period throughout the Holocene, with the bottom of the diagram representing the transition from the Late Glacial to Early Holocene. This transition is marked by a shift from the characteristic dominant vegetation *Betula, Juniperus,* Cyperaceae and Poaceae to a wider expanse of tree species such as *Corylus, Pinus, Salix* and *Quercus*, and a decrease in herbaceous species, signifying a shift from open ground to woodland. The low presence of aquatic vegetation at Borheen Lough at the start of the record suggests that climatic conditions were cold. The subsequent shift in vegetation described above suggests an increase in soil moisture and a change to milder more humid conditions. This is supported by low loss on ignition values, which suggests high rates of erosion in the catchment area and unsettled edaphic conditions. The three largest fire events are represented on the diagram by three red lines. It is difficult to see any unifying trends in vegetation change following these events; a decrease in *Corylus* coincides with the two events at approx. 1000BP, subsequently followed by a large increase in the taxa. The same trend exists for *Calluna* where all three fire events coincide with a decrease in the taxa and then a subsequent increase. *Calluna* is a good indicator of blanket bog growing in the lake catchment and this may be where these local fires were occurring, rather than at lower altitudes where tree populations dominate. Poaceae tends to be associated with decreases following the latter two events which may indicate that this taxa was being negatively impacted by fire here. Looking at the sum of tree and herb species to the

right of the diagram the two fire events at approx. 1000BP coincide with a large decrease in tree and shrub taxa, while the latter event coincides with a smaller dip in abundance. Microscopic charcoal represented here appears to increase in the Medieval and Modern periods, which suggests that burning was increasing in the wider landscape towards the present day. Other common trends in vegetation change are identified here and can be seen in pollen diagrams throughout Ireland; the decline in *Pinus* here occurs slightly earlier than at other sites in this study at approx. 5400BP. Major decreases in Scots pine abundance are thought to be caused by climate deterioration leading to surface wetness, and impacts can be seen throughout Ireland and the British Isles during the mid-Holocene (Hall et al., 1994, Bennett, 1984, Birks, 1975, Bradshaw and Browne, 1987). The abundance of *Pinus* remains low throughout the rest of the sequence, only beginning to re-emerge slightly in the Late Holocene to approx. 4% abundance. The decline in *Ulmus* also occurs at this time and is one of the most enigmatic features of pollen diagrams across North-West Europe. It has been hypothesised to be due to disease, climate or human activity or a combination thereof, and has been associated with a climatic shift to more continental climatic conditions, involving colder winters and warmer summers (Parker et al., 2002).The expansion of *Alnus* can also be seen in this diagram at approx. 7000BP which is thought to coincide with a period of climatic wetness signifying the transition from the Boreal to Atlantic period (Bennett and Birks, 1990). From the Neolithic towards the present day, there is an increase in anthropogenic indicators, such as *Plantago, Rumex,* Cyperaceae and Cereal which indicate agricultural activity within the surrounding landscape. There is a significant decrease in *Pediastrum*, a disturbance indicator, at this time may indicate a change in the status of the lake, namely a change from eutrophic to oligotrophic, possibly induced by climate or anthropogenic change (Pannard et al., 2008). The increase in herb communities (Poaceae and Cyperaceae) also supports the idea of a climate change as their presence suggests an increase in soil

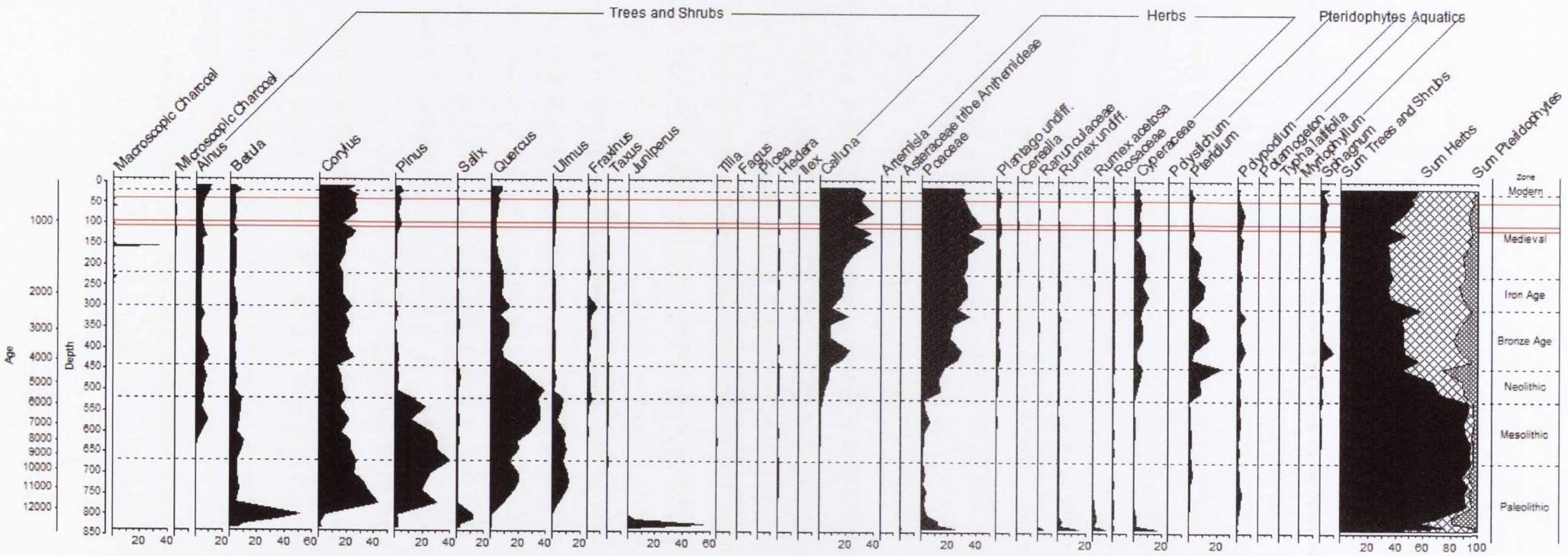


Figure 6.1.5 Pollen diagram from Borheen Lough, red lines represent three largest fire events, Macroscopic and Microscopic charcoal are represented as concentration (pieces cm^{-3}).

moisture content and a change to milder more humid conditions towards the present day.

Diheen Lough

Diheen Lough is located approx. 1km to the west of Borheen Lough at an altitude of 554m. The two lakes are separated by Galteebeg peak and lie on top of a bedrock of Old Red Sandstone. The pollen record from Diheen Lough is shorter than the other sites in this analysis covering only two time periods, the Modern and Medieval, towards the end of the Holocene. The three largest fire events identified here are represented by red lines on the pollen diagram. The earliest fire event at approx. 400BP occurs where there has been a decrease in the dominant vegetation *Corylus* and *Calluna*, and an increase in Poaceae and *Sphagnum*. The middle fire event at approx. 280BP also occurs where there is decreased values of *Corylus*. Following this fire event Poaceae decreases, and in contrast to the previous fire event is also followed by an increase in *Calluna* and an increase in *Pediastrum*. The most recent fire event at approx. 180BP is followed by marked decreases in Poaceae and the continued decrease in *Pediastrum*, with marginal increases in *Calluna* and *Corylus*. Overall all three events are associated with decreases in the sum of trees, and smaller decreases in the sum of herbs. The vegetation distribution here is similar to that identified at Borheen Lough, an adjacent site within the Galty Mountains. The dominance of *Corylus, Calluna* and Poaceae towards the present day indicates a change in soil moisture content and a shift to more humid conditions. The low values of *Pinus* and *Ulmus* here suggest the characteristic declines have occurred further back in time, similar to other sites throughout Ireland, and at Borheen Lough at approx. 5400BP. The reintroduction of *Pinus* which occurred during the 18th Century, can be seen at the top of this diagram where *Pinus* increase from approx. 200BP (Roche et al., 2009). A significant change in *Pediastrum* is identified at both Diheen Lough and Borheen Lough where it decreases from approx. 700BP. This genus is a

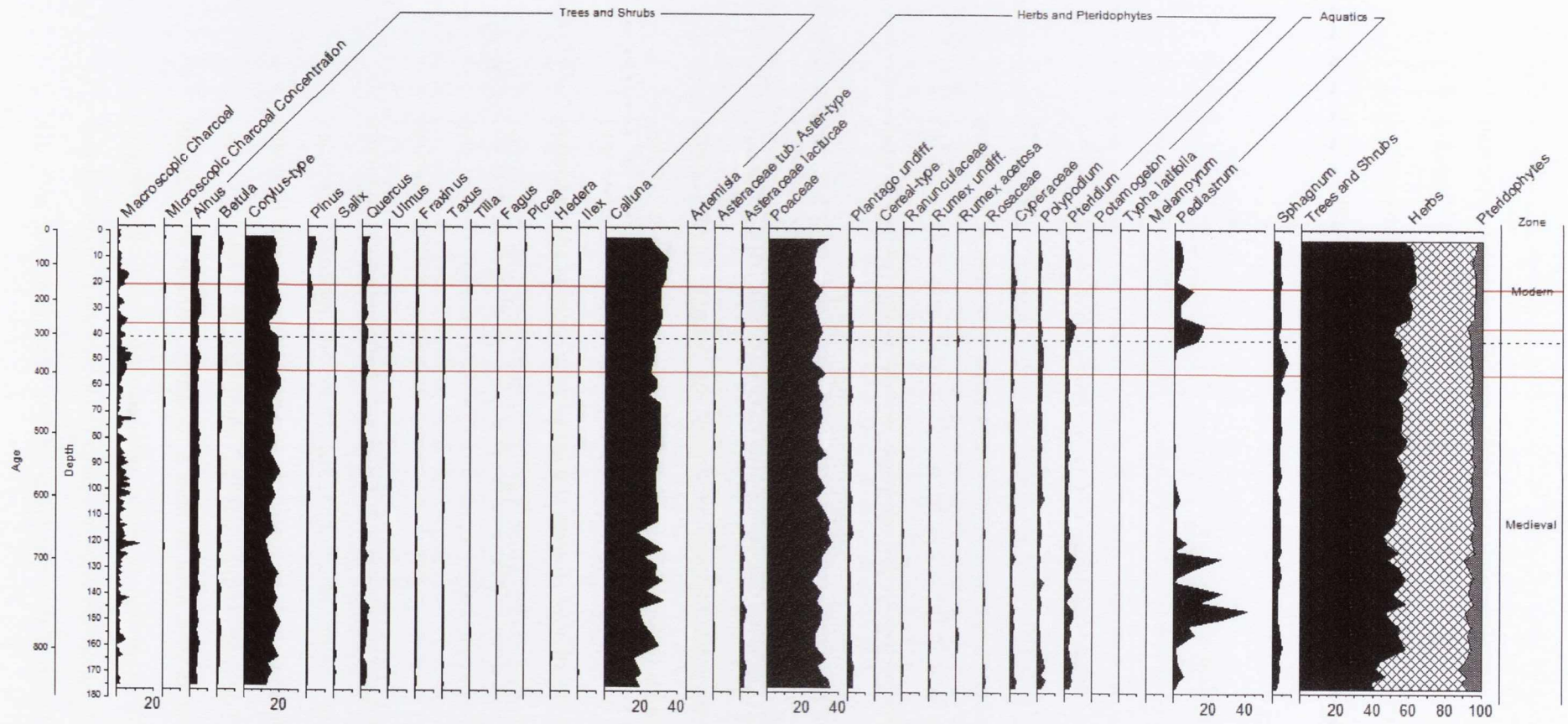


Figure 6.1.6 Pollen diagram from Diheen Lough, red lines represent three largest fire event, Macroscopic and Microscopic charcoal are represented as concentration (pieces cm^{-3}).

disturbance indicator (Pannard et al., 2008) and the decrease at Diheen Lough follows one of the identified fire events. The change may indicate a change in the status of the lake, namely a change from eutrophic to oligotrophic, possibly induced by climate or anthropogenic change.

Wicklow Mountains

Kelly's Lough

Kelly's Lough is located within the Lugnaquilla Complex within the Wicklow Mountains and lies at an elevation of 585m atop a bedrock of Granite. The pollen data from Kelly's Lough covers the entire Holocene from the Palaeolithic to the present day, and can be seen represented in Figure 6.1.7. The bottom of the diagram represents the transition from the Younger Dryas, with the expansion of thermophilous taxa such as *Juniperus, Betula, Salix* and Poaceae. Late-glacial sediment was not found at this site and this is consistent with other cirque lakes from Ireland, indicating that they accumulated ice during the Younger Dryas (Coxon, 2001). The Mesolithic period is dominated by tree taxa such as *Corylus, Pinus, Quercus* and *Ulmus*, with species such as *Calluna,* Poaceae and Cyperaceae remaining low. During the Mesolithic there is also evidence of the 8.2ka climate event which signifies a shift to colder conditions (Ghilardi and O'Connell, 2013) represented by a decrease in *Corylus* and *Quercus* and an increase in *Betula* and *Pinus* at approx. 8200BP. Typical vegetation changes can be seen here that are represented in sediments from throughout Ireland (Mitchell, 1996). There are noticeable declines in *Pinus* and *Ulmus* during the Neolithic and Bronze Age, coinciding with the *Pinus* decline and *Ulmus* decline identified at numerous sites throughout Ireland, and here at Kelly's Lough at 4400BP and 5200BP respectively. An expansion in *Alnus* was also observed beginning at approx. 7000BP, which has been attributed to increased climate wetness (Lowe, 1993). The fact that the *Pinus* decline is synchronous with the

expansion in *Alnus* suggests that it replaced *Pinus* within valley systems due to waterlogged conditions (Bennett, 1984). Three of the largest fire events identified at Kelly's Lough are represented on the pollen diagram by red lines. A number of trends can be identified that are associated with these events; there is an increase in *Corylus* within 50 years following fire, with a decrease in other tree species such as *Pinus and Quercus*. Alnus also decreases following the first and third fire events. Charcoal is consistently present throughout the diagram increasing slightly during the Iron Age and Medieval periods. Loss on ignition also decreases immediately following these events, while herbaceous taxa such as Poaceae, Cyperaceae and *Sphagnum* appear largely unaffected. Microscopic charcoal represented here increases in abundance in the Medieval and Modern periods, similar to previous sites discussed, suggesting an increase in fire activity in the wider landscape towards the present day. Moving towards the present day there is a transition from a dominance of tree taxa to a dominance in *Calluna,* Poaceae and *Sphagnum*, with only two trees, *Corylus* and *Alnus* remaining significantly present. This is concurrent with expansion of peatland at Kelly's Lough which is evident from 6500BP (Leira et al., 2006), and other species begin to appear which confirm this, *Erica, Narthecium, Menyanthes* and *Potentilla.* Indicators of human activity such as *Plantago,* Cyperaceae and *Rumex* generally increase from the Neolithic towards the present day, and coincides with the expansion of open pasture within the landscape with the rise in grasses and the decrease in tree taxa.

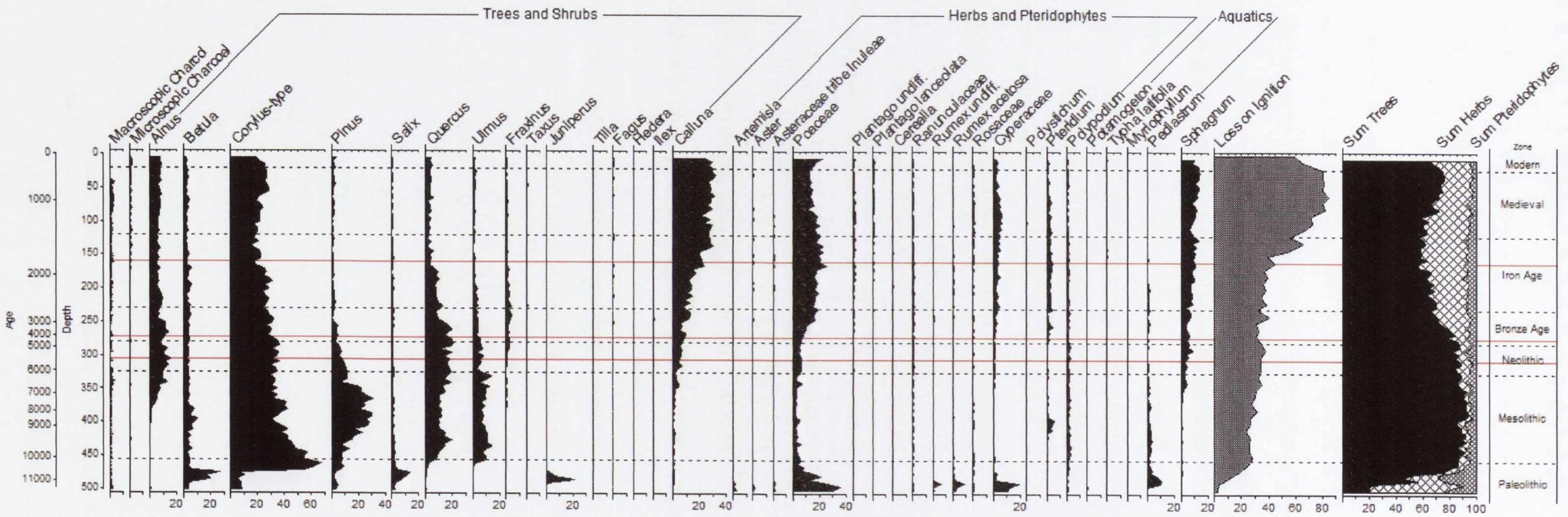


Figure 6.1.7 Pollen diagram from Kelly's Lough, red lines represent identified fire events, Macroscopic and Microscopic charcoal are represented as concentration (pieces cm^{-3})

6.5.2 Spearman's Correlation

A Spearman's correlation was carried out between the charcoal concentrations at each of the study sites and compared with selected taxa, and the percentage of tree and herbaceous species. The rho and p-values from this analysis can be seen in Table 6.1. The significant correlations vary between sites and between taxa. *Calluna* produced the highest number of significant correlations, with negative rho values at Cuckoo and Sheheree Lough, and a positive values at Ballinderry and Borheen Lough. As charcoal increases at Ballinderry and Borheen Lough *Calluna* also increases, whereas as charcoal increases at Cuckoo and Sheheree Lough, *Calluna* decreases. *Pinus, Quercus*, Poaceae and *Corylus* all produced significant correlation at three study sites. *Pinus* and Poaceae at Borheen, Cuckoo and Sheheree Lough. *Quercus* at Ballinderry, Cuckoo and Sheheree Lough; and *Corylus* at Cuckoo, Kelly's and Sheheree Lough. The largest number of significant correlations were identified at Sheheree Lough, with p-values less than 0.01, and only one taxon *Pteridium*, not producing a significant result. Borheen and Cuckoo Lough also produced a large number of significant results, both with 6 results with p-values less than 0.05. The large number of significant correlation here suggests that fire was having a more pronounced impact on the vegetation at these sites. Two sites Cornaher and Diheen Lough produced no significant correlations, perhaps indicating that fire was not impacting the vegetation composition here. This analysis was carried out using the charcoal concentration at corresponding pollen depths. A similar analysis was carried out to test the correlation between the selected taxa and the charcoal concentration calculated as a three point moving average. Charcoal records contain noise and a three point moving average smooth's this noise to potentially provide more accurate results. This analysis produced remarkably similar results to the previous analysis. It produced the same significant correlations at Borheen and

Sheheree Lough, and both analyses identified no significant relationship between the specified taxa and charcoal at Cornaher and Diheen Lough. The moving average correlation did produce an additional significant relationship at Ballinderry Lough, where Poaceae was flagged as having a significant negative correlation. At Cuckoo Lough and Kelly's Lough this method produced one less significant correlation than the previous method, omitting *Corylus* at Cuckoo Lough and *Sphagnum* at Kelly's Lough. Correlation matrices were drawn to illustrate selected relationships between charcoal and specific taxa at each site and Figure 6.2.1 shows an example of these figures for Borheen and Sheheree Lough. The graph displays the rho value of the correlation and the level of significance represented by stars in the top portion of the graph. A positive value indicates a positive correlation i.e. as one variable increases so does the other. A negative value indicates a negative correlation i.e. as one variable increases the other decreases. The stars represent the significance level, with one star indicating a level of 0.1, two stars indicating a level of 0.05 and three stars indicating the highest significance with a level of 0.01. The middle of the graph displays histograms of the selected taxa with kernel density overlays. This shows a bar graph of the raw data associated with each variable, showing basic information such as central point, width of spread and shape. The kernel density overlay provides a smoothed curve of the data estimating the probability density function. Finally the bottom of the graph shows the bivariate scatterplots for each relationship and a line of best fit and is a useful summary of data.

Table 6.1 Spearman's Correlation results charcoal concentration vs selected species with significant results in red

Study Site	Result	Pinus	Quercus	Alnus	Calluna	Sphagnum	Poaceae	Pteridium	Plantago	Corylus	%Trees	%Herbs
Ballinderry	Rho	-0.31786	-0.64389	0.0154	0.46549	0.14568	-0.36136	0.242765	0.13221	-0.3638	-0.1082	0.09351
	p-value	0.1136	0.0004	0.9404	0.0166	0.4776	0.0697	0.2321	0.5197	0.0677	0.5987	0.6496
Borheen	Rho	-0.359	-0.24811	0.55797	0.39788	-	0.5175	0.3886	0.60083	0.106814	-0.4596	0.50279
	p-value	0.0291	0.1387	0.00033	0.01474	-	0.00104	0.0175	0.0000	0.5292	0.0042	0.00151
Cornaher	Rho	0.00534	0.05567	0.07882	-0.01926	0.09839	-0.09197	0.06318	0.06363	0.21015	0.10756	-0.1076
	p-value	0.9698	0.6921	0.5748	0.8911	0.4833	0.5125	0.6531	0.6508	0.1309	0.4433	0.4433
Cuckoo	Rho	0.55902	0.43997	-0.0405	-0.30573	-0.08426	-0.34019	0.27239	-0.15189	0.21974	0.38553	-0.3876
	p-value	0.0000	0.0000	0.693	0.00232	0.4119	0.00065	0.00695	0.1375	0.03057	0.0000	0.0000
Diheen	Rho	0.0083	-0.10899	0.02258	0.03398	0.15442	-0.06839	-0.1729	-0.0742	0.08489	-0.0042	-0.0272
	p-value	0.9553	0.4597	0.8787	0.8183	0.2947	0.6432	0.2398	0.6162	0.5651	0.9774	0.8539
Kellys	Rho	-0.18912	-0.14845	0.02886	0.18957	0.19751	0.18843	0.26224	0.18995	-0.21716	-0.1903	0.21213
	p-value	0.0595	0.1405	0.7756	0.05888	0.04888	0.0605	0.00839	0.0584	0.02999	0.0579	0.03411
Sheheree	Rho	0.3159	0.59713	0.4506	-0.4273	-0.4077	-0.5283	-0.02332	-0.3261	0.4748	0.56867	-0.5686
	p-value	0.000	0.000	0.000	0.000	0.000	0.0000	0.7697	0.000	0.000	0.000	0.0000

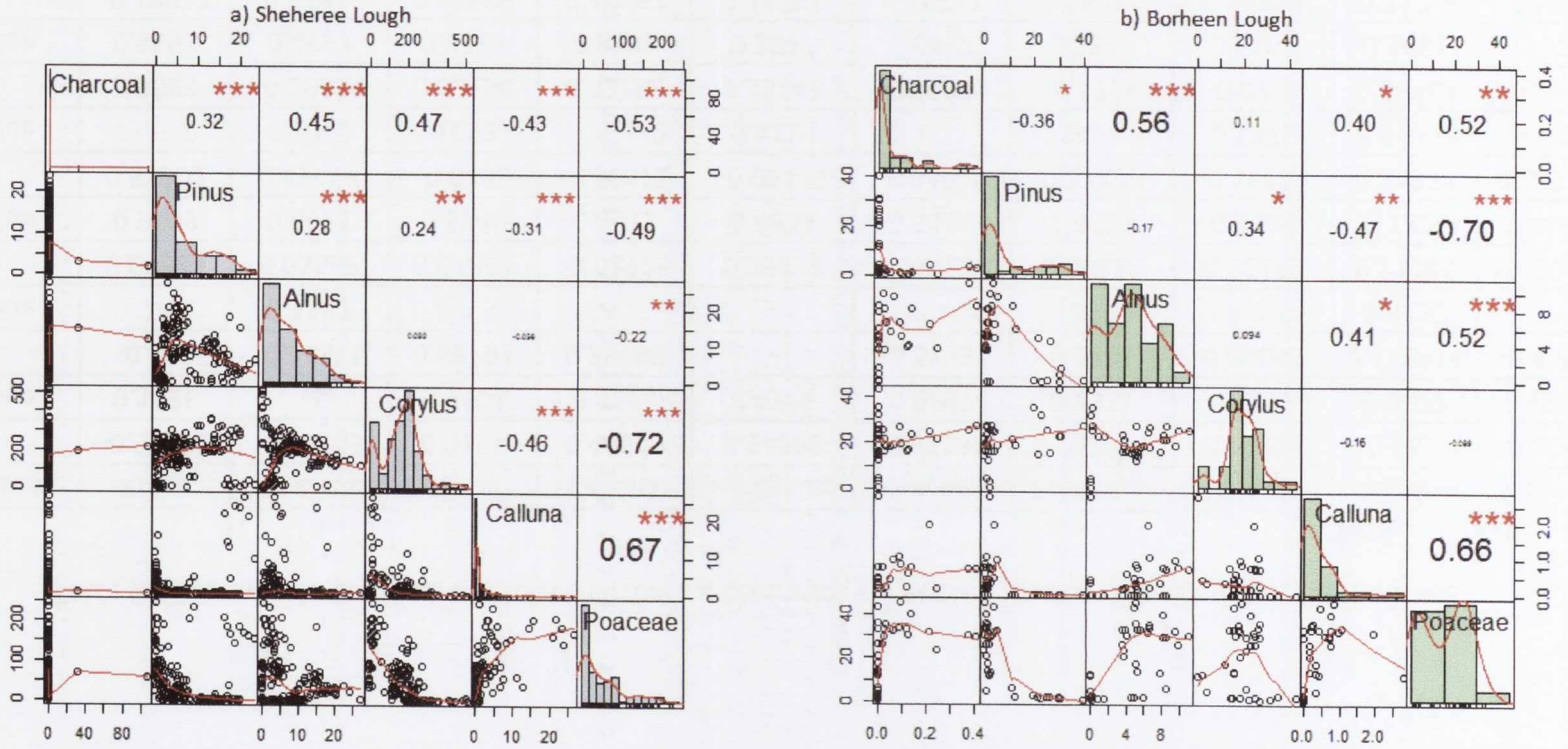


Figure 6.2. Correlation Matrices for Borheen and Sheheree Lough

Top: rho values and their significance level Middle: histogram of selected taxa and kernel density overlay Bottom: Scatterplot and line of best fit

6.5.3 Rate of Change Analysis

The rate of change and the smoothed rate of change with a three point average were calculated for each of the study sites and plotted with the identified fire events, and can be seen overleaf Figure 6.3. The rate of change varies significantly between study sites. At Ballinderry Lough the largest peaks in rate of change can be seen to coincide with two of the identified fire events at approx. 60cm and 110cm depth. Four distinct periods of high rate of change can be seen in an almost cyclic manner moving from a depth of 220cm to the present day with the cycles spanning approx. 50 years. This is in contrast to the record from Borheen Lough which displays a more linear trend throughout the record with two small peaks occurring post fire events at 150cm and 225cm. This trend is similar to the records from Kelly's where there is also a largely linear trend throughout the record. There is a period of higher rate of change at Kelly's Lough from 250-100cm depth, which coincides with three of the identified fire events. At Sheheree Lough there are peaks in rate of change associated with fire events at the bottom of the record at approx. 550cm, with phases of linear rate of change towards the present day. The records from Cornaher and Diheen Lough display more dramatic changes in rate of change. The largest peak at Cornaher Lough is associated with one of the identified fire events at approx. 550cm. The remaining fire events clustered around 300cm depth are preceded by a large peak in rate of change, and followed by a smaller peak. Diheen Lough shows a high frequency of rate of change and three large peaks between 140 and 120 cm depth and can be seen associated with three identified fire events. There is however another large peak here which is not associated with a fire event. The remaining part of the record although containing fire events, the rate of change remains low with smaller peaks towards the present day. The rate of change at Cuckoo Lough shows a high peak at approx. 25cm which does not coincide with any identified fire events,

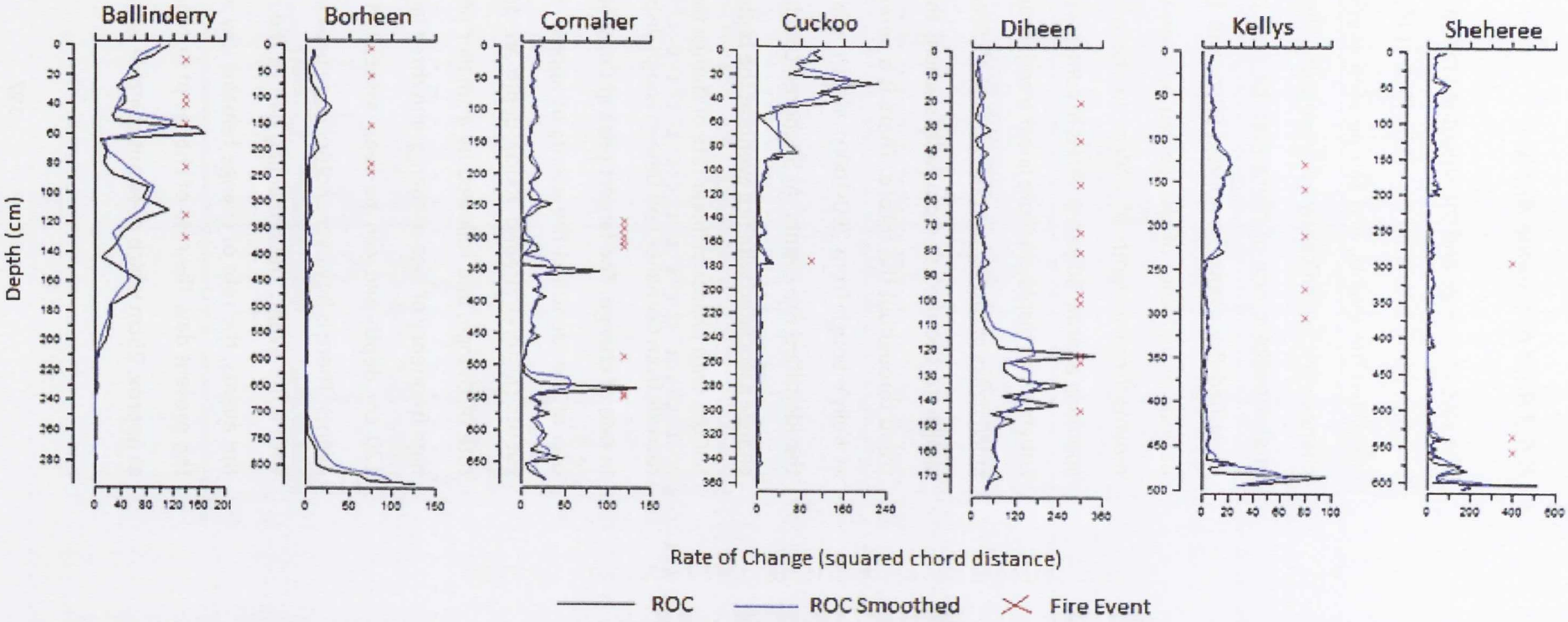


Figure 6.3 Rate of Change multi-plot for each study site showing rate of change, rate of change smoothed and identified fire events.

but is close to the present day. The rest of the record displays lower values with small peaks occurring at 152cm and 180cm with the latter being associated with the single fire event represented here.

6.5.4 NMDS Ordination

Three NMDS ordinations were produced for each study site, representing the individual pollen depths, archaeological periods and occurrence of fire events using the Bray-Curtis index. Two sets of PERMANOVA analyses were also carried out for each site to identify differences between the archaeological periods and the occurrence of fire events. The results for each site are discussed below.

Irish Midlands

Ballinderry Lough

The ordinations from Ballinderry Lough can be seen in Figure 6.4.1 Graph a) displays the stressplot associated with the ordination calculations. The fit of the points around the line are reasonably good, with a linear fit R^2 of 0.799. The best solution reached in this analysis was drawn with 2 axes, and the final stress calculated as 14.4 which is low enough to be reliably interpreted. The final instability was calculated as 0.0006 and the maximum residual was 0.002. Graph b) shows the ordination of pollen sample depths. The present day is represented as zero with the furthest point back in time at 10,650BP. Evidence can be seen of three distinct phases, where pollen samples are clustered between 50BP and 650BP, and again between 1000BP and 2000BP where the points are clustered to the right of axis 1. The final phase from 2,500BP to the bottom of the record is more widely space along axis 1, suggesting that these points are less similar than the previous depths discussed. Graph c) presents the different archaeological periods overlaid in the ordination space. The Modern and Mesolithic period represent time periods where the points

are clustered close together. The Palaeolithic, Neolithic and Bronze Age period are represented by a single point here. The Iron Age and Medieval periods display the most variation and represent a large proportion of the data points, which are scattered more widely throughout the ordination space. The final plot Graph d) shows the distribution of identified fire events, represented by the blue triangles. The events appear to be largely concentrated within the Medieval period and are quite closely spaced, especially on axis 2. Table 6.2.1 below shows the PERMANOVA results for the archaeological periods and fire events. The p-value here for the archaeological periods suggest that the null hypothesis should be rejected and there is a significant difference between the different archaeological periods within the ordination. This is in contrast to the test on the fire events which produces a p-value>0.05 indicating that the null hypothesis should be accepted and there is no difference between fire events.

Table 6.2.1 PERMANOVA results examining difference between archaeological periods and fire events at Ballinderry Lough.

PERMANOVA	Degrees of Freedom	Sum of Squares	Mean Squares	F.Model	R^2	Pr(>F)
Data$Period	6	1.45	0.24	3.34	0.36	0.001***
Data$Fire	1	0.06	0.06	0.57	0.01	0.734

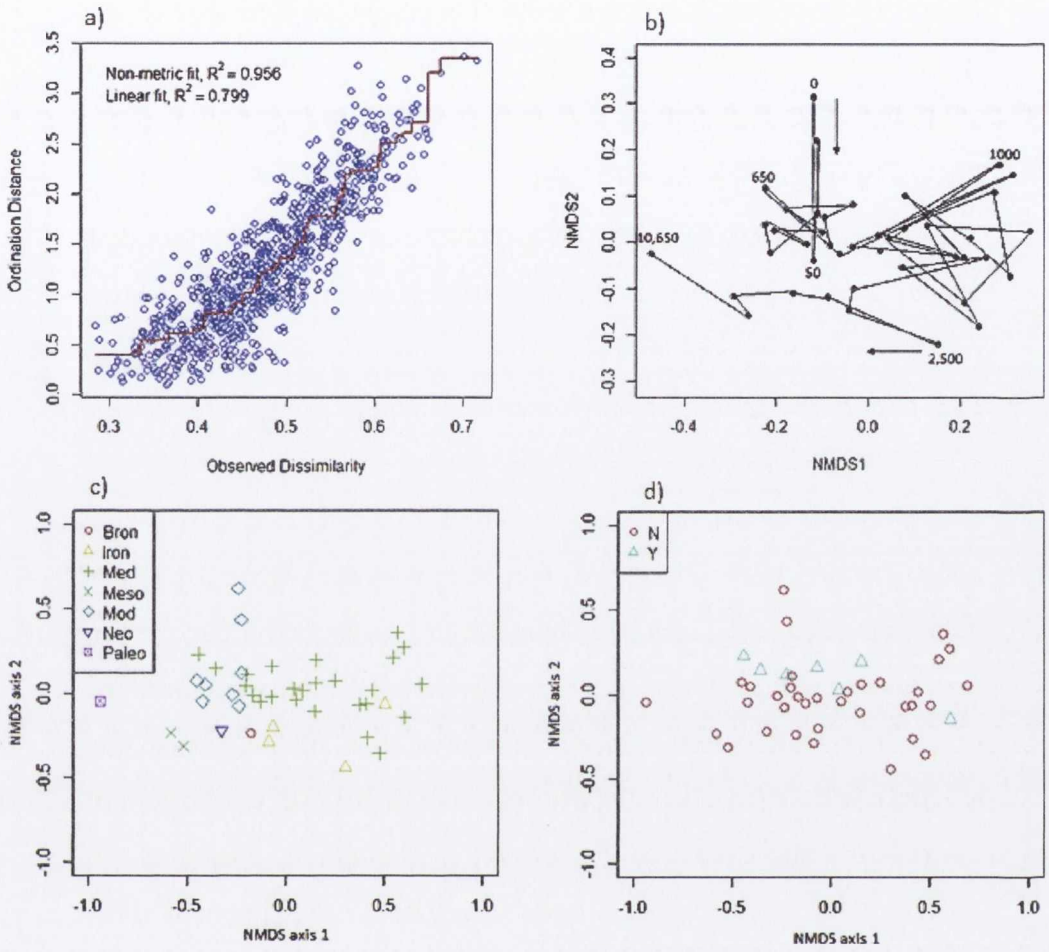


Figure 6.4.1 Ballinderry Lough; a) NMDS Ordination Stressplot b) NMDS Ordination with vectors joining samples in chronological order, numbers refer to years cal BP c) NMDS Ordination with Archaeological Periods overlaid d) NMDS Ordination with Fire Events overlaid, Y represents fire event, N no fire event

Cornaher Lough

Figure 6.4.2 overleaf shows the ordination graphs for Cornaher Lough. Graph a) represents the stressplot for Cornaher Lough which again shows a good fit and a linear fit value of R^2=0.919. The best solution reached for this ordination produced 2 axes and a negligible final stress of 8.1. The final instability was calculated as 0.0002 and the maximum residual was 0.001. Graph b) displays the ordination of pollen samples, and two distinct clusters can be identified. From the present day represented as zero to 1,700BP there is a linear cluster of points. Then from approx. 2000BP to 8000BP there is a circular cluster of points. The point at 5100BP stands out as significantly different from the other surrounding pollen samples here. Looking at the pollen diagram (Figure 5.1.2) this point coincides with a dramatic increase in *Corylus* and a decrease in *Quercus* and *Ulmus*. Similar to the records from Ballinderry and Borheen Lough, from 8000BP to the bottom of the record at 10650BP the points are more widely spaced and appear to curve round with the bottom of the record being closest to the present day. Graph c) represents the ordination of archaeological periods. Similar to the previous sites discussed the periods are relatively well clustered together, but as you move further back in time the points begin to become more widely spaced, with the largest variation here occurring within the Mesolithic. Finally graph d) represents the occurrence of fire events, and they are more widely distributed at this site with 4 events occurring close together in the Bronze Age and the remaining events occurring in the Mesolithic. Table 6.2.2 below shows the PERMANOVA results for the archaeological periods and fire events. The p-value here of 0.001 for the archaeological periods indicates that the null hypothesis should be rejected and there is a significant difference between the different archaeological periods. In contrast the p-value of 0.235 for the fire events indicated that the null hypothesis should be accepted and there is no difference between the fire events. The p-value here is however lower

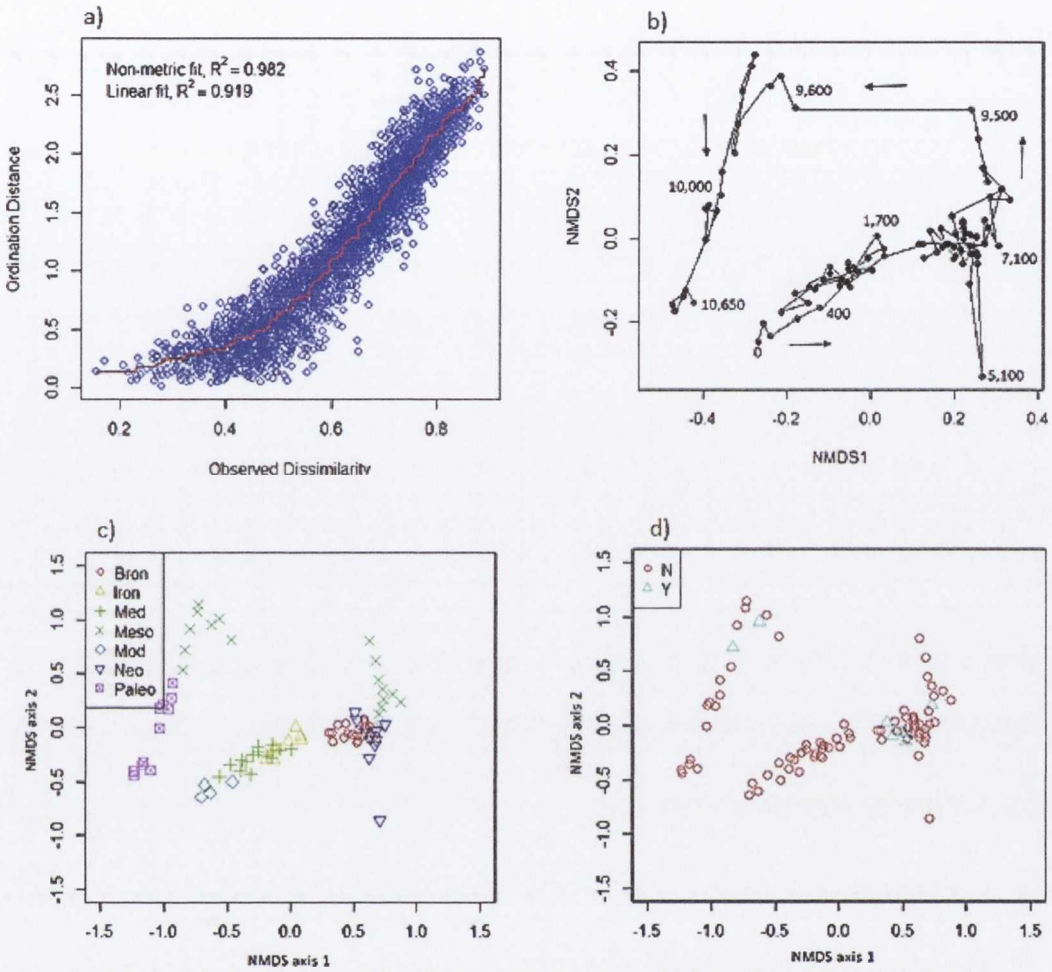


Figure 6.4.2 Cornaher Lough; a) NMDS Ordination Stressplot b) NMDS Ordination with vectors joining samples in chronological order, numbers refer to years cal BP c) NMDS Ordination with Archaeological Periods overlaid d) NMDS Ordination with Fire Events overlaid, Y represents fire event, N no fire event

than the previous two sites due to the slightly wider distribution of fire events.

Table 6.2.2 PERMANOVA results examining difference between archaeological periods and fire events at Cornaher Lough.

PERMANOVA	Degrees of Freedom	Sum of Squares	Mean Squares	F.Model	R^2	Pr(>F)
Data$Period	6	8.75	1.46	20.78	0.60	0.001***
Data$Fire	1	0.22	0.22	1.32	0.01	0.235

Killarney National Park

Cuckoo Lough

The ordination plots for Cuckoo Lough can be seen in Figure 6.4.3. The stressplot here (graph a) has a wider distribution of points than the previous sites but still displays a good fit with a linear fit value of R^2=0.78. The best solution for the NMDS calculations resulted in two axes, with a final stress value of 14. The final instability was calculated as 0.0008 and the maximum residual was 0.006. Graph b) shows the ordination plot for the pollen samples. This ordination appears denser than those from previous sites. The present day is represented by zero and can be seen to be closest to approx. 13000BP. There is a high concentration of points ranging from 3500BP to 8500BP. After which the points become more widely spaced and appear to curve round ending in a cluster of points at the bottom of the record from 14,000BP to 15,300BP. A number of points

stand out as significantly different at 13,350BP, 11000BP and 700BP. Graph c) represents the ordination of archaeological periods. Most periods are clustered quite closely together, similar to other study sites. The most widely distributed periods are the Palaeolithic and Medieval. The ordination of fire events are represented in Graph d). Only one fire event is represented here that covers a similar time span as the pollen data, and it occurs in the Neolithic time period. Table 6.2.3 below displays the results of the PERMANOVA analysis comparing the different archaeological periods and fire events. The p-value of 0.001 for the archaeological periods indicates that the null hypothesis should be rejected and there is a significant difference between the time periods. The p-value of 0.931 representing the fire events indicates that the events are similar and the null hypothesis should be accepted which is not surprising as there is only one fire event represented at this site.

Table 6.2.3 PERMANOVA results examining difference between archaeological periods and fire events at Cuckoo Lough.

PERMANOVA	Degrees of Freedom	Sum of Squares	Mean Squares	F.Model	R^2	Pr(>F)
Data$Period	6	4.01	0.67	18.45	0.55	0.001***
Data$Fire	1	0.03	0.03	0.44	0.005	0.931

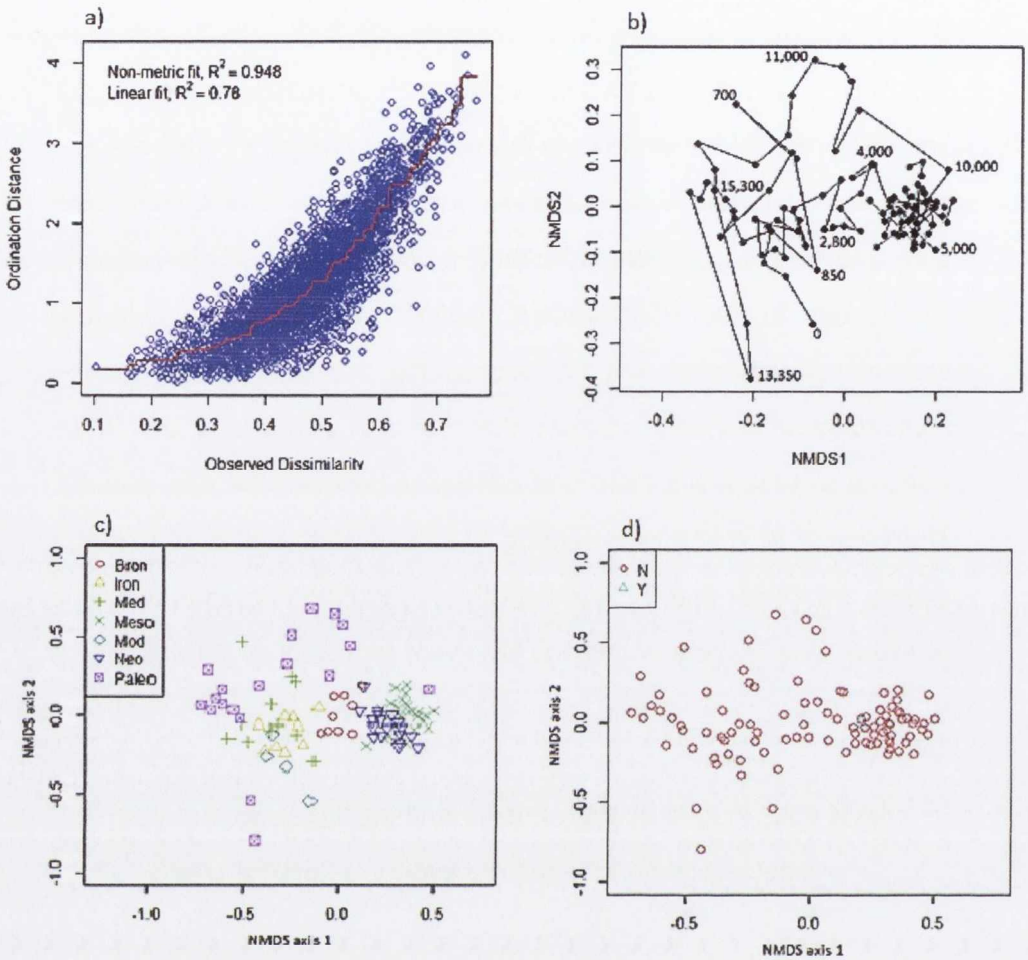


Figure 6.4.3 Cuckoo Lough; a) NMDS Ordination Stressplot b) NMDS Ordination with vectors joining samples in chronological order, numbers refer to years cal BP c) NMDS Ordination with Archaeological Periods overlaid d) NMDS Ordination with Fire Events overlaid, Y represents fire event, N no fire event

Sheheree Lough

Figure 6.4.4 shows the ordination plots from Sheheree Lough. Graph a) displays the stressplot for the ordination, the points are well fitted to the trend line and this is backed up with a linear fit value of R^2=0.931. The best solution reached for this ordination produced 2 axes and a negligible final stress of 10.4. The final instability was calculated as 0.00004 and the maximum residual was 0.0003. Graph b) shows the ordination plot for each pollen sample, and displays similar trends to previous sites. The present day represented by 0BP stands out as significantly different at this site, and is closest to 10200BP and 1250BP. There are a number of periods which can be identified where the points are significantly clustered, between 600BP and 1000BP, and between 2000BP and 9000BP. After which the points are more widely spaced within the ordination space from 9000BP to the bottom of the record at 9950BP. A number of points stand out as significantly different, occurring at 350BP, 920BP and 1000BP. Graph c) represents the ordination of archaeological periods. A number of the periods are clustered closely together i.e. the Neolithic, Bronze Age, Iron Age and Modern periods. The remaining time periods, the Medieval and Mesolithic are more widely distributed throughout the ordination space. Finally graph d) represents the ordination of the identified fire events at Sheheree Lough. Only three events occur at this site and are in adjacent time periods. Table 6.2.4 below shows the results from the PERMANOVA analysis examining the differences between the archaeological periods and between the fire events at Sheheree Lough. The comparison between the archaeological periods produced a p-value of 0.001 indicating that the null hypothesis should be rejected and there is a significant difference between the various time periods. The comparison of the fire events produced a p-value slightly larger than the critical value of 0.05 indicating that the events are similar and the null hypothesis should be accepted.

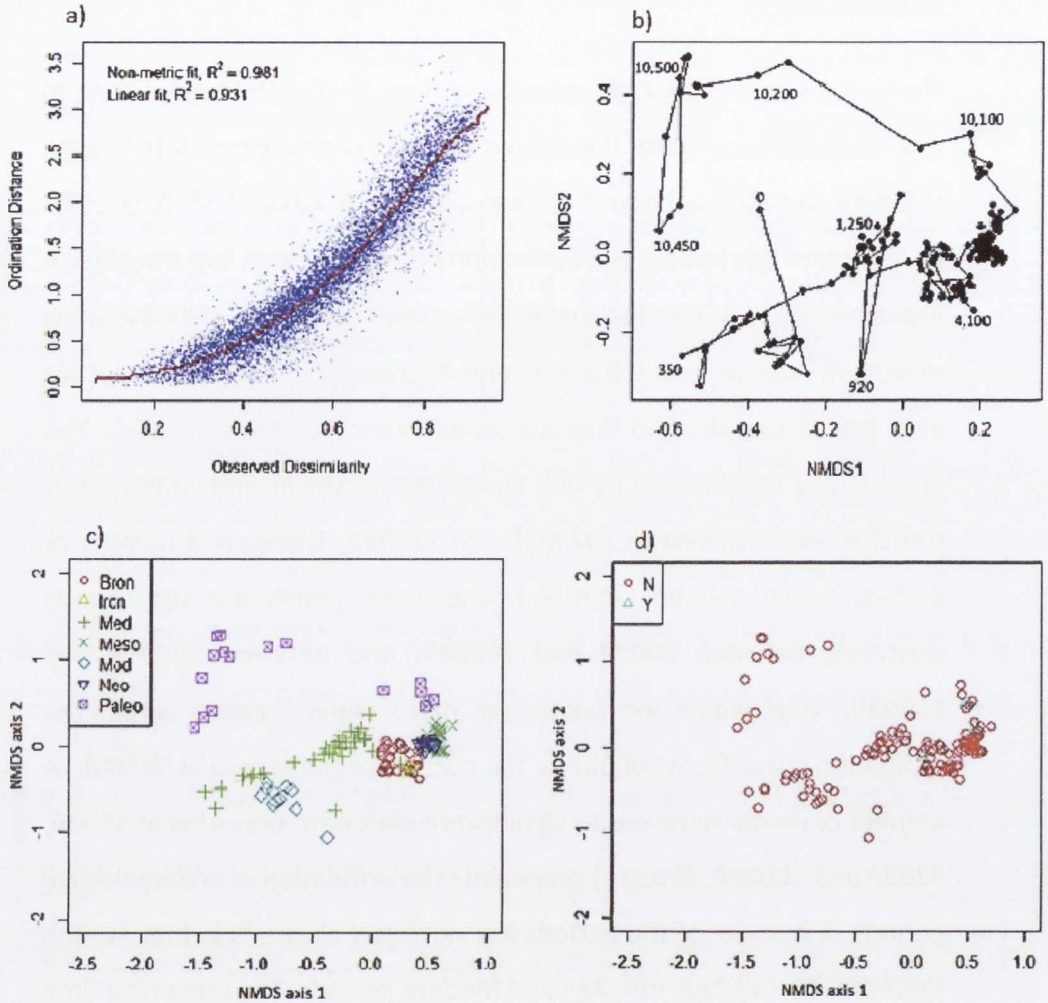


Figure 6.4.4 Sheheree Lough; a) NMDS Ordination Stressplot b) NMDS Ordination with vectors joining samples in chronological order, numbers refer to years cal BP c) NMDS Ordination with Archaeological Periods overlaid d) NMDS Ordination with Fire Events overlaid, Y represents fire event, N no fire event

Table 6.2.4 PERMANOVA results examining difference between archaeological periods and fire events at Sheheree Lough.

PERMANOVA	Degrees of Freedom	Sum of Squares	Mean Squares	F.Model	R^2	Pr(>F)
Data$Period	6	14.22	2.37	36.7	0.59	0.001***
Data$Fire	1	0.14	0.14	0.96	0.01	0.388

Galty Mountains

Borheen Lough

The ordination for Borheen Lough can be seen in Figure 6.4.5. Graph a) represents the stressplot for the ordination at Borheen Lough, and the fit of the points is extremely good with a linear fit value of R^2=0.944. The best solution for the NMDS calculation produced 2 axes, and a final stress of 9.2 which allows for a reliable interpretation. The final instability was calculated as 0.001 and the maximum residual was 0.005. Graph b) shows the ordination of pollen samples. The present day is represented as zero and is located at the bottom of the ordination plot. It is clustered with a number of points, one of the closest representing 3500BP. As the record moves to 4200BP the points become more widely spaced before a further group of points between 5600BP and 10500BP located close together. From 11000BP to the end of the record at 12,800 there is a very wide spacing of ordination points, with the bottom depth looping round to coincide with points representing between 5000BP and 7000BP.Graph c) represents the ordination plot of archaeological

periods. Most periods are clustered relatively close together, but the further back in time it appears the more widely spaced the points become. The Palaeolithic at the beginning of the Holocene displays the most widely spaced points within the ordination space. Finally graph d) represents the ordination of occurrence of fire events at this site. Similar to at Ballinderry Lough the events appear to be concentrated in the Medieval and Iron Age periods, and are very closely spaced with the ordination plot. Table 6.2.5 below shows the PERMANOVA results for the archaeological periods and fire events. The p-value for the archaeological periods (p-value 0.001) suggests that there is a significant difference between the various periods and the null hypothesis should be rejected. This is in contrast to the fire event result which has a p-value 0.734 greater than the critical value of 0.05 suggesting that the fire events are similar and the null hypothesis should be accepted.

Table 6.2.5 PERMANOVA results examining difference between archaeological periods and fire events at Borheen Lough.

PERMANOVA	Degrees of Freedom	Sum of Squares	Mean Squares	F.Model	R^2	Pr(>F)
Data$Period	6	2.94	0.49	6.54	0.54	0.001***
Data$Fire	1	0.32	0.32	2.44	0.06	0.734

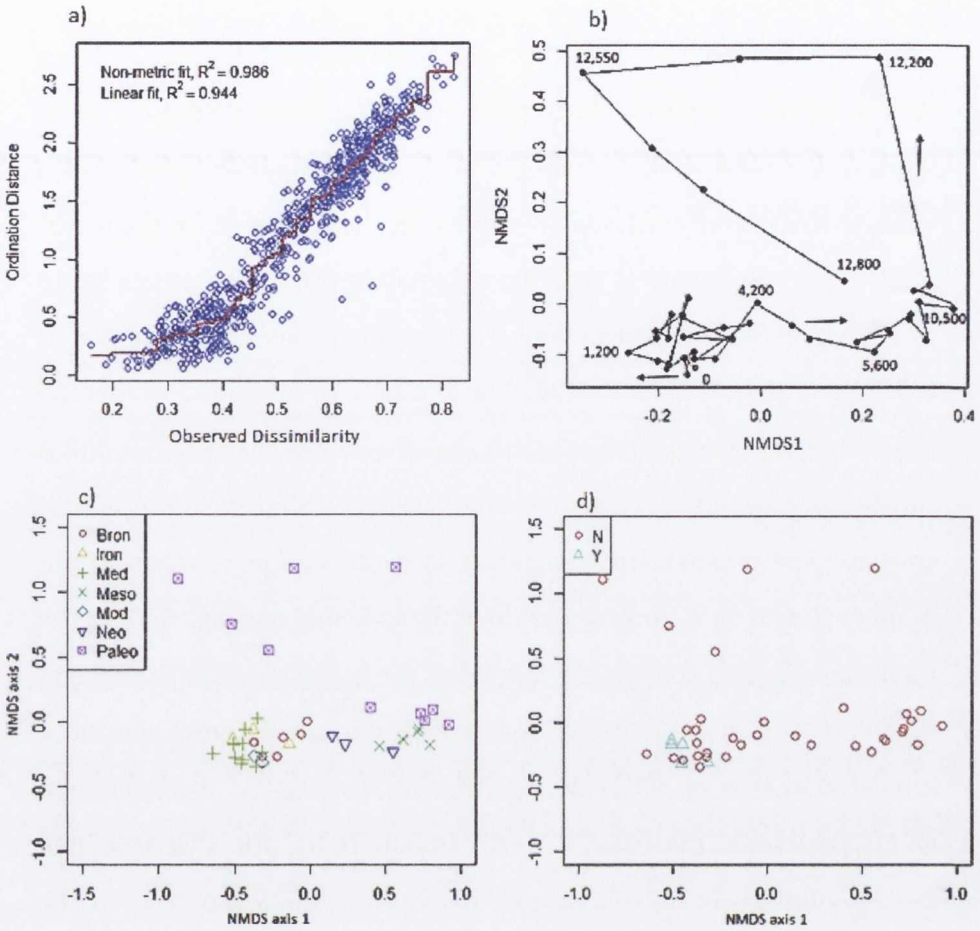


Figure 6.4.5 Borheen Lough; a) NMDS Ordination Stressplot b) NMDS Ordination with vectors joining samples in chronological order, numbers refer to years cal BP c) NMDS Ordination with Archaeological Periods overlaid d) NMDS Ordination with Fire Events overlaid, Y represents fire event, N no fire event

Diheen Lough

The ordination plots for Diheen Lough can be seen in Figure 6.4.6 Graph a) displays the stressplot for Diheen Lough, the points here are quite widely distributed and not as good a fit as at previous sites. This is reflected by the linear fit value R^2=0.594. The best solution for the NMDS calculation resulted in 2 axes with a relatively low final stress of 13 providing reliable reconstructions. The final instability was calculated as 0.0002 and the maximum residual was 0.0009. Graph b) represents the ordination of pollen samples for this site. The overall shape of this plot is similar to previous sites for the Medieval and Modern time periods covered. The present day is represented by a value of zero and in this graph is closest to the bottom depth dated to 860BP and also 530BP. The points are densely compact to the left of the graph between 100BP and 600BP. A number of points stand out as significantly different and these are dated to approx. 700BP and 750BP. Graph c) displays the ordination of archaeological periods at Diheen Lough. There are only two time periods represented at this site, the Medieval and Modern periods. The points from the Modern period are well clustered towards the bottom of the ordination space, whereas the points from the medieval period are more widely scattered. Finally graph d) represents the ordination of fire events characterized by blue triangles. Four events are closely spaced within the ordination plot and represent fires within the Medieval period. The remaining four events are more widely distributed and represent events occurring in both the Modern and Medieval period. Table 6.2.6 below shows the results from the PERMANOVA analysis examining differences between archaeological periods and fire events. The p-value 0.024 associated with the archaeological periods indicates that the periods are significantly different and the null hypothesis should be rejected. In terms of the fire events the p-value of 0.256 indicates that the null hypothesis should be accepted, indicating that the fire events at Diheen Lough are similar.

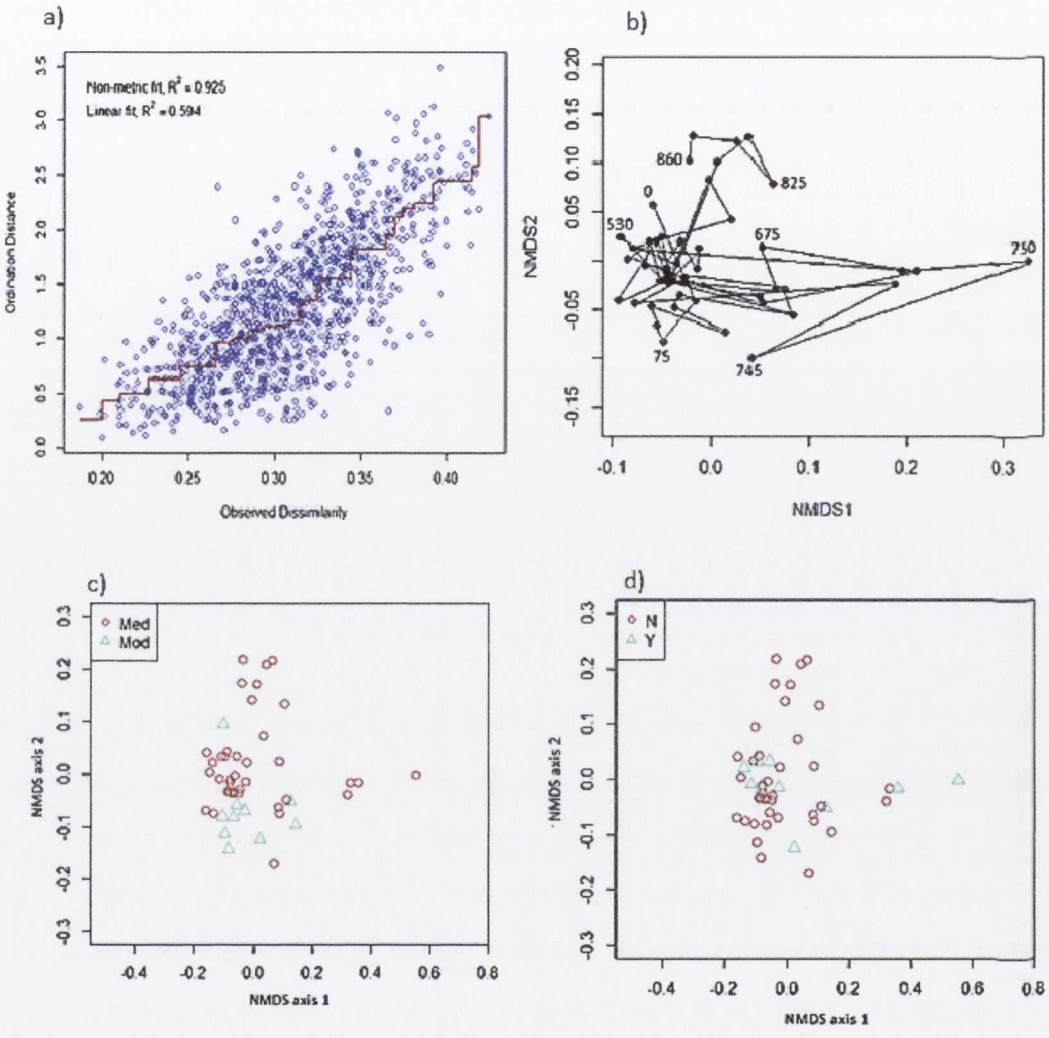


Figure 6.4.6 Diheen Lough; a) NMDS Ordination Stressplot b) NMDS Ordination with vectors joining samples in chronological order, numbers refer to years cal BP c) NMDS Ordination with Archaeological Periods overlaid d) NMDS Ordination with Fire Events overlaid, Y represents fire event, N no fire event

Table 6.2.6 PERMANOVA results examining difference between archaeological periods and fire events at Diheen Lough.

PERMANOVA	Degrees of Freedom	Sum of Squares	Mean Squares	F.Model	R^2	Pr(>F)
Data$Period	1	0.05	0.05	2.74	0.55	0.024*
Data$Fire	1	0.02	0.02	1.21	0.03	0.256

Wicklow Mountains

Kelly's Lough

The ordination plots from Kelly's Lough can be seen in Figure 6.4.7. The stressplot here displayed in Graph a) represents a very good fit of points to the trend line with a liner fit value of R^2=0.94. Two axes were found to be the best solution from the NMDS calculations, and a final stress of 6.7 was recorded. The final instability was calculated as 0.00009 and the maximum residual was 0.0005. Graph b) shows the ordination plot representing the different pollen samples. This graph show three distinct clusters of points; the first around the present day 0BP to 1800BP, then from 2000BP to 3100BP and finally from 5300BP to 7100BP. These groups of points are located towards the bottom of the ordination plot. As the points move further back in time from 7200BP to the bottom of the record at 11,075BP, the points become more widely spaced in the ordination plot, and they stand out as significantly different from the first part of the record. The graph here indicates that the present day is most similar to samples from the Modern and Medieval periods. Graph c)

represents the ordination of archaeological periods. Most archaeological periods are clustered very close together within the ordination space, with the Mesolithic and Palaeolithic being more widespread than the other periods. Finally graph d) represents the ordination of fire events at Kelly's Lough. The fire events are all clustered close together towards the bottom of the ordination space, and are spread throughout a range of archaeological periods. Table 6.2.7 below represents the PERMANOVA results examining the differences between the archaeological periods and the identified fire events. The difference between the archaeological periods is significant with a p-value of 0.001 indicating that the null hypothesis of equality should be rejected. This is in contrast to the results comparing the fire events which produced a p-value of 0.464 which indicates the fire events are similar and the null hypothesis should be accepted.

Table 6.2.7 PERMANOVA results examining difference between archaeological periods and fire events at Kelly's Lough.

PERMANOVA	Degrees of Freedom	Sum of Squares	Mean Squares	F.Model	R^2	Pr(>F)
Data$Period	6	6.93	1.15	34.45	0.69	0.001***
Data$Fire	1	0.079	0.079	0.78	0.008	0.464

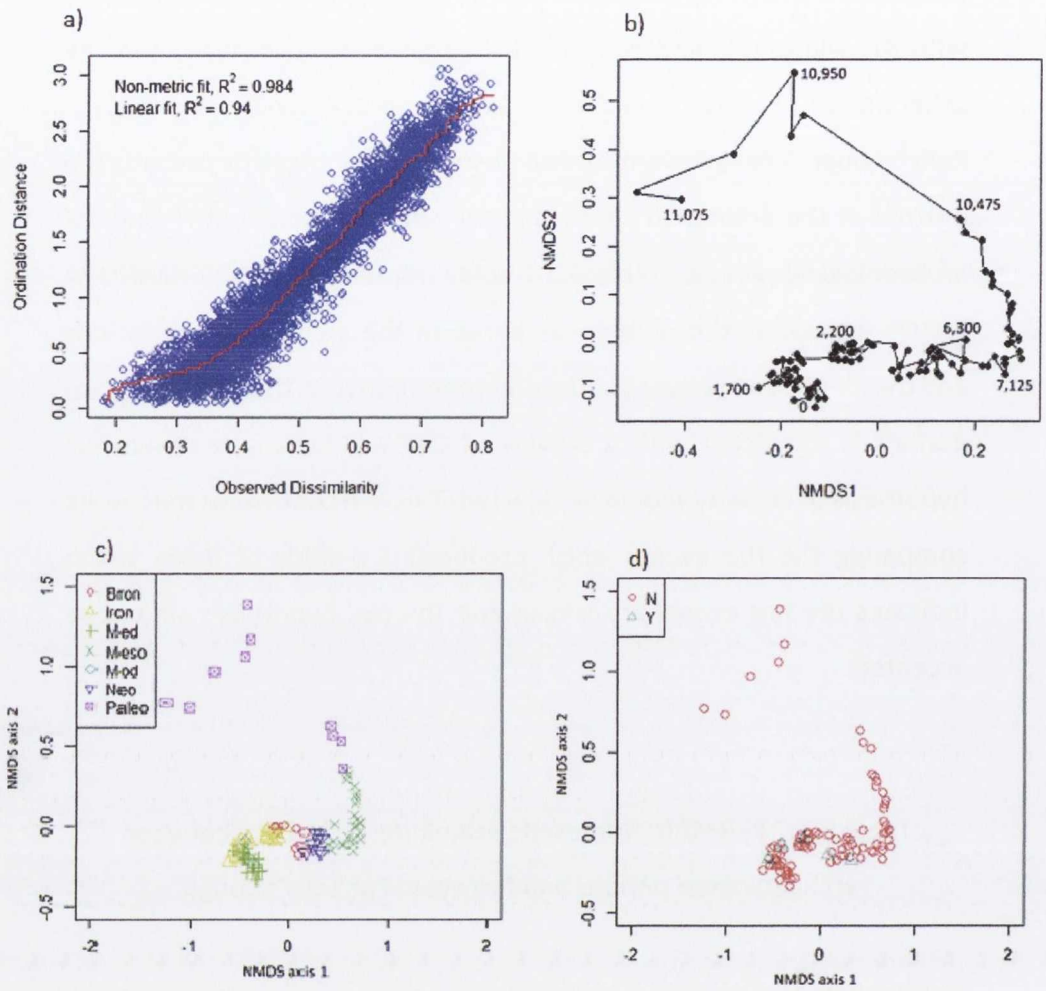


Figure 6.4.7 Kelly's Lough; a) NMDS Ordination Stressplot b) NMDS Ordination with vectors joining samples in chronological order, numbers refer to years cal BP c) NMDS Ordination with Archaeological Periods overlaid d) NMDS Ordination with Fire Events overlaid, Y represents fire event, N no fire event

6.5.5 Paired T-Test

To analyse whether certain taxa are significantly impacted by fire, the vegetation composition before and after each fire event was compared using a paired t-test. The data from each study site was composited and compared in a 200 year time window in R under the null hypothesis of equality of averages. The results can be seen in Table 6.3. A number of significant results were produced indicating that fire events were affecting vegetation. The largest number of significant results were obtained from *Salix* and *Sphagnum* which were significant at Diheen and Sheheree Lough, and Ballinderry and Diheen respectively. *Calluna*, *Plantago* and *Pteridium* also produced significant results at Diheen Lough with p-values less than the critical value of 0.05. Diheen Lough therefore produced the largest number of significant results out of all the study sites. The data were compiled and a t-test carried out to the unified effect of fire on each taxon, but only one taxon *Salix* produced a significant value, indicating that fire was impacting *Salix* within Ireland.

6.5.6 Multi-Response Permutation Procedure

MRPP analysis was carried out for each of the study sites, to test whether there is a significant difference between the vegetation between two or more of the archaeological time periods. The results from these analyses can be seen in Table 6.4 and 6.5. Each of the study sites produced significant results from the MRPP analysis indicating that the archaeological time periods are different. All sites produced a p-value of 0.001, except for Diheen Lough which produced a p-value of 0.007. The A values presented give an indication of the size of the differences identified, with the lowest values for Ballinderry and Diheen Lough indicating that there was the least difference between archaeological

periods at these sites. The rest of the study sites displayed similar A values ranging from 0.3494 at Borheen Lough to 0.4654 at Kelly's Lough. The previous PERMANOVA backs up these results producing a p-value for each study site equal to 0.001, except for at Diheen Lough where the p-value was 0.024. These results clearly indicate that the vegetation distributions within each archaeological time period differed more than expected by chance and the values can be seen in Table 6.4. Table 6.5 shows additional data from the MRPP analyses at each of the sites. The delta values are presented and represent the overall weighted mean of the group mean distances, and n represents the number of observations in each group. The Palaeolithic show the largest Delta values for five of the study sites (Borheen, Cornaher, Cuckoo, Kelly's and Sheheree Lough), indicating that this time period differs the most. While at Ballinderry and Diheen Lough the Medieval period has the largest Delta values and stands out as the most different from the other time periods.

Table 6.3 T-test results examining how selected taxa change before and after a fire event, significant results in red.

Taxa	Pinus	Quercus	Salix	Plantago	Poaceae	Betula	Corylus	Alnus	Calluna	Sphagnum	Pteridium	Trees	Herbs
Ballinderry	0.167	0.722	0.368	0.111	0.660	0.113	0.914	0.698	0.186	0.001	0.241	0.329	0.858
Borheen	0.647	0.615	0.423	0.504	0.661	0.300	0.616	0.921	0.445	0.446	0.668	0.878	0.966
Cornaher	0.612	0.819	0.329	0.570	0.163	0.305	0.099	0.934	0.176	0.244	0.237	0.321	0.321
Cuckoo	0.265	0.598	NA	0.5	0.772	0.237	0.411	0.653	0.684	0.916	0.340	0.508	0.582
Diheen	0.114	0.352	0.000	0.030	0.357	0.287	0.629	0.518	0.000	0.029	0.003	0.406	0.004
Kellys	0.587	0.125	0.066	0.874	0.879	0.330	0.230	0.789	0.075	0.757	0.625	0.529	0.497
Sheheree	0.233	0.670	0.045	0.552	0.253	0.061	0.232	0.806	0.381	0.871	0.472	0.523	0.523
All Sites	0.198	0.714	0.028	0.113	0.805	0.175	0.243	0.832	0.344	0.859	0.261	0.971	0.502

Table 6.4 Results from MRPP analysis at each study site

Study Site	A	Observed delta	Expected dellta	significance	Permutations
Ballinderry	0.1425	0.3618	0.4219	0.001	999
Borheen	0.3494	0.3157	0.4852	0.001	999
Cornaher	0.4136	0.3116	0.5313	0.001	999
Cuckoo	0.3358	0.2439	0.3672	0.001	999
Diheen	0.0249	0.1812	0.1859	0.007	999
Kellys	0.4654	0.2164	0.4047	0.001	999
Sheheree	0.4108	0.2933	0.4977	0.001	999

Table 6.5 showing delta values for each period and weight of each group (n) from MRPP analysis

Study Site	Modern	Medieval	Bronze Age	Iron Age	Neolithic	Mesolithic	Palaeolithic
Ballinderry	0.21 n=8	0.38 n=25	-	0.37 n=4	-	0.21 n=2	-
Borheen	0.14 n=2	0.22 n=10	0.26 n=6	0.22 n=3	0.26 n=3	0.21 n=2	0.59 n=10
Cornaher	0.24 n=4	0.25 n=14	0.19 n=21	0.20 n=9	0.29 n=10	0.56 n=18	0.33 n=11
Cuckoo	0.25 n=4	0.28 n=11	0.19 n=9	0.20 n=9	0.19 n=18	0.20 n=27	0.38 n=19
Diheen	0.15 n=10	0.18 n=39	-	-	-	-	-
Kellys	0.14 n=3	0.13 n=20	0.19 n=10	0.19 n=22	0.14 n=9	0.21 n=26	0.56 n=10
Sheheree	0.18 n=36	0.12 n=4	-	0.23 n=41	0.11 n=11	0.38 n=42	0.67 n=16

6.6 Discussion

Fire is a dominant ecological process and an integral part of many ecosystems (Pausas and Vallejo, 1999). It affects all aspects within the environment fostering climate change, vegetation change, disease and other forms of disturbance (Clark et al., 1996, Swetnam and Betancourt, 1998). Fire has been increasing in recent years, in its scale and intensity and level of destruction (Marlon, 2013), seen not only on a global and national scale, but locally within Ireland (Nugent, 2015). It has been difficult for society to accept that wildfire is an important and increasing issue within Ireland, given the nature of our weather and climate. However given the frequency and severity of recent wildfire incidents, this should be taken as a warning signal, as wildfires are predicted to increase in intensity in the future with increased climate change (Flannigan, 2009). It is therefore important to study how fire has affected ecosystems and vegetation within Ireland in the past to help mitigate and manage negative future impacts.

This study has identified the impact of wildfire on the vegetation and surrounding landscape at seven sites spread throughout Ireland. Pollen analysis was carried out and pollen diagrams produced to represent the vegetation transitions at each site. The sites displayed similar patterns in vegetation composition with respect to geographical location and archaeological period. The sites can be divided into uplands (Borheen, Diheen and Kelly's Lough) and lowlands (Ballinderry, Cornaher, Cuckoo and Sheheree Lough), with similar vegetation patterns displayed at these sites. This is backed up by similar ordination patterns specific to each archaeological period represented across the sites. There are characteristic events which are picked up across the majority of sites e.g. the decline in *Pinus* is represented at sites which cover this time period and has declined across all sites by approx. 4000BP. The elm decline is also apparent and occurs at approx. 5500BP at sites which cover this time

period. The vegetation transition from the late Glacial to early Holocene is also represented at a number of sites, Borheen, Kelly's, Sheheree and Cornaher Lough, and is characterised by a shift from a dominance of *Juniperus, Betula* and Poaceae to a dominance of *Corylus, Pinus, Quercus* and *Ulmus*. These events are characteristic of many Irish pollen diagrams.

The effect of fire on specific taxa was also examined across all of the sites, and a number of relationships emerged. *Corylus* was identified to increase following fire events at a number of sites; including Borheen, Cornaher, Diheen and Kellys Lough. While *Corylus* can be seen to dominantly increase following fire events there are occasions where a decrease in abundance is recorded, especially at Sheheree and Cuckoo Lough. The dominant increase in *Corylus* post-fire is not surprising as it has previously been characterised as a somewhat fire tolerant species (Tinner et al., 2000, Huntley, 1993) re-sprouting and spreading well after fire (Tinner et al., 1999, Huntley, 1993).

Another species which has been identified in this study to increase following fire events is *Alnus*. Increases can be seen at Borheen, Cornaher, Diheen and Kelly's Lough, with decreases noted at Sheheree and Cuckoo Lough. *Alnus* appears to follow a similar pattern of behaviour as *Corylus*, and has been designated as a fire-enhanced species (Tinner et al., 2000). Lantz et al. (2010) also found that *Alnus* is likely to respond to increased temperature with elevated alder growth and reproduction following fire, indicating its influence on the population dynamics.

Looking at the record for *Betula* across all of the sites, the effect of fire on *Betula* is less pronounced than the previous species discussed, however a number of increases post fire are observed at Ballinderry, Cornaher, Diheen and Sheheree. The *Betula* curve at Borheen Lough shows no significant impact, while at Cuckoo Lough there is a decrease in *Betula* immediately post-fire. Tinner et al. (1999) also reported temporary increases in *Betula* following wildfire and Reyes et al. (1997)

found that it is often one of the first species to colonise the landscape post-fire, however it does not depend on fire for its establishment.

Quercus has been previously identified as a possible fire resistant species whose thick bark may give some protection against fires (Mason, 2000). Niklasson et al. (2002) and Tinner et al. (2000) identified that *Quercus* was largely unaffected by wildfire, with Benito Garzón et al. (2008) recording an unprecedented decline in *Quercus*. Colombaroli et al. (2007) also revealed through cross correlations that fire was hindering the expansion of *Quercus*. These studies are in line with the results from this analysis which shows fire having little impact on *Quercus* at Ballinderry, Borheen and Diheen Lough, with small decreases occurring at Cuckoo, Kelly's and Sheheree Lough. A significant decrease in *Quercus* was observed at Cornaher lough which is associated with the largest peak in micro-charcoal. These results suggest that *Quercus* is dominantly fire resistant to moderate wildfires, showing a marked decline as fire size and intensity increases.

Pinus has been observed in this analysis to increase following fire events across the majority of study sites. In addition *Pinus* has been found to be one of the best adapted trees to survive fire in Killarney National Park with its thick resinous bark (Quirke, 2001). It has also been seen to regenerate successfully following wildfire in Europe (Vacchiano et al., 2013, Zin et al., 2015, Matías and Jump, 2012, Beghin et al., 2010). Often being one of the first to colonise after a fire (Thomas and McAlpine, 2010), as pine cones have a serotinous quality allowing them to spread readily post fire (Johnson and Gutsell, 1993).

Ulmus has been identified as a fire damaged species in Europe, with fire effects slowly leading to localised extinction (Tinner et al., 2000, Tinner et al., 1999). Declines can be seen in elm from numerous sites in this study, Cornaher, Cuckoo, Diheen, Kelly's and Sheheree Lough associated with identified fire events. Decreases in *Ulmus* can also be seen

associated with fire throughout the Holocene in the Alps (Tinner et al., 2005, Wick and Möhl, 2006).

Stanley (1999) describes Poaceae as a fire adapted and fire tolerant family, with fire benefitting grasses by killing taller competitors and maximizing the light and nutrients that grasses can obtain. Fires of a lower magnitude and intensity are less likely to damage basal grass meristems and subterranean grass roots and rhizomes, permitting them to rapidly sprout after a fire, intercept light, occupy space, and recycle nutrients before competitors can become established (Clarke and French, 2005). Looking at the pollen evidence from the sites in this analysis, Poaceae exhibits a varied response to fire. Increases post-fire can be seen at a number of sites including Ballinderry, Borheen and Kelly's Lough, however decreases post-fire appear to be more frequent, especially at Cornaher, Cuckoo, Diheen and Sheheree Lough. This would suggest that the response of *Poaceae* to fire is related to the fires magnitude and size, as its effect varies both between and within sites throughout Ireland.

Bradshaw et al. (1997) identified a strong correlation between the presence of *Calluna* pollen and charcoal fragments from sites in Finland, Sweden, Denmark and Ireland. Within this study where represented *Calluna* shows a varied response to fire events. At Cuckoo and Kelly's Lough there are small increases in *Calluna* post-fire, but at Ballinderry and Diheen Lough fires are followed by marked decreases in the abundance of *Calluna*. Måren et al. (2010) suggest that burning is highly important for heathland management, with increased levels of *Calluna* pollen and charcoal found at numerous sites along the Atlantic coast of Norway (Prøsch-Danielsen and Simonsen, 2000, Odgaard, 1992). The varied response displayed in Ireland may suggest that fire is not the dominant factor effecting *Calluna* here and at a number of sites it is not present in significant abundance to warrant an adequate response.

To further examine the relationship between fire and specific vegetation a Spearman's correlation was carried out between charcoal concentration and abundance of selected taxa. Five study sites returned significant results, Ballinderry, Borheen, Cuckoo, Kelly's and Sheheree Lough. The type of correlation varied not only between species but between study sites e.g. *Pinus* shows a strong negative correlation at Borheen Lough but displays a positive correlation at Cuckoo Lough and Sheheree Lough. It was highlighted in the pollen analysis that species response to fire varies both within study site and between sites, which may account for the differences in the correlation analysis. Cuckoo Lough and Sheheree Lough, both located within Killarney National Park, were identified as having an alternative response to fire on a number of occasions i.e. while *Alnus* and *Quercus* increases following fire at the other study sites it is observed to decrease at Cuckoo and Sheheree Lough. The sites in Killarney are at a lower altitude and have a wetter climate, in comparison with the other sites, which may have contributed to the differences here.

It is clear from this multisite analysis that fire effects vegetation in different ways depending not only on study site, as there are also variations in species response within site. This suggests that the effect of fire on vegetation is controlled by various factors relating to the conditions of the plant, such as fuel availability, moisture content and fire resilient characteristics. While also being influenced by environmental factors such as weather, climate, drought or disease, and anthropogenic activity.

To help identify which species are significantly altered by fire, a t-test was carried out on composite before and after each fire event in a 200 year time window. A number of species did not change significantly post fire and can perhaps be characterised as fire resistant species. *Alnus, Pinus Quercus, Betula, Corylus and* Poaceae produced no significant results across all of the study sites, suggesting that these taxa are not

significantly impacted by fire. *Calluna, Pteridium and Plantago* produced a significant result at one study site, suggesting that largely they are unaffected by fire in the Irish landscape. However at specific sites under local conditions or more intense fires, they may be a greater influence. *Sphagnum* and *Salix* are seen to be impacted the most by fire, showing a significant response at 2 sites each. Therefore these taxa can be classed as more prone to change following a fire event. A composite record of trees and herbs was also examined and herbs were found to have a significant response at Diheen Lough. This is likely to be influenced by the response of individual taxa but highlights a site where the overall taxa were significantly impacted by fire.

To further examine vegetation transitions and fire responses, the MRPP analysis was carried out to identify if vegetation change was taking place between each of the archaeological time periods at each of the study sites. This analysis was unified across all of the study sites with a significant p-value less than 0.05 indicating that there is a difference between the vegetation compositions in each of the archaeological time periods. This is what is expected as the pollen diagrams illustrate constant variance in species abundance throughout the Holocene.

To examine the relationship between the vegetation composition and fire events at the different pollen depths and archaeological time periods, an ordination analysis was carried out and a number of graphs produced to represent the different variables. From this analysis a number of similar trends have emerged across all of the study sites; the vegetation compositions represented within each archaeological time period are significantly different from one other. This can be seen in the graph c) ordination plots and in the significant p-values produced via the PERMANOVA analysis. A similar PERMANOVA analysis also identified that the fire events at each of the study sites are similar, and generally occur clustered together within the ordination plot (graph d). This would suggest that similar conditions were prevailing when a fire event

occurred. The ordination plots also acknowledged that the further back in time i.e. pre 9,000BP, the more likely the samples are to be significantly different from adjacent samples. This can be seen displayed in the ordination plots, graph b) of Sheheree, Kelly's, Cornaher and Borheen Lough where the samples at the bottom of the record are more widely distributed within the ordination space. This is also true looking at the distributions representing archaeological periods, where there is a marked disparity in the points representing the Palaeolithic time period at these sites. This suggests that there was significant and more rapid change taking place during the early Holocene, reflected here in the vegetation composition, possibly due to the dramatic increase in temperature throughout Europe following the last ice age (Davis et al., 2003). The ordination plots can also indicate which reconstruction of past conditions is most similar to the present day. This is the point located closest to the value of zero (representing the present day) on the ordination plots graph b). These plots show in the case of at least three study sites, specifically Cornaher, Cuckoo and Sheheree Lough, the present day was adjacent to samples representing the Early Holocene, between 10,000 and 13000BP. As stated previously the early Holocene was a period of rapid environmental change, and the fact that the modern samples from these sites correlates with such reconstructions, suggests that similar conditions or patterns of change are occurring in recent years under the pressure of climate change or anthropogenic activity. It also reflects the largely open and treeless nature of the current landscape which was evident in the late glacial and early Holocene. At four of the study sites, Ballinderry, Borheen, Diheen and Kelly's Lough the majority of fire events are occurring close to the present day, suggesting that fire has been increasing in recent years at these sites and occurring in periods where climate and vegetation conditions were similar.

To analyse periods of instability throughout the Holocene, a rate of change analysis was carried out at each of the study sites. The highest

periods of change appear to be associated with identified fire events, although the magnitude of change varies from site to site. There are a number of peaks of ROC which are not associated with any fire events i.e. from 100cm to the top of the record at Cuckoo Lough. This change may be due to another factor affecting the vegetation at this site, such as an increase in climate change or anthropogenic activity. The records vary from site to site with little synchroniety between high rate of change periods at similar study sites. The period of high rate of change from 120-150cm at Diheen Lough predates a smaller peak in rate of change at Borheen lough at 125cm by approx. 200 years. Both sites are located within the Galty Mountains and contain a similar vegetation composition. Whereas the largest period of rate of change at Cuckoo Lough, predates any peaks in rate of change identified at Sheheree Lough, both located within Killarney National Park. This analysis suggests that fire events were having a significant impact on the vegetation composition at each of the study sites, reflected by the peaks in rate of change. This is supported by Mitchell (2013) who carried out a rate of change analysis on composite records from 4 sites and demonstrated that the highest rate of change throughout the Holocene was associated with the highest peak in charcoal accumulation, dated between 1 and 1000BP. The fact that adjacent sites do not show a similar pattern of rate of change suggest that fires and their effects were more localised directly adjacent to the lake, not affecting the wider landscape.

One of the challenges in fire history reconstruction is determining whether the source of ignition was natural or anthropogenic. There are fire events at Cornaher, Cuckoo and Sheheree Lough which predate human colonisation in the area and can therefore be attributed to natural causes. However as you move closer to the present day it is more difficult to decipher. The Medieval period stands out as having increased fire activity and was a period of increased temperature and human activity. The taxa discussed here are responding in different ways at

different study sites within the same archaeological periods in their response to fire, making it difficult to identify any unified patterns. It is clear that further study in this area is necessary and should be in conjunction with modern analyses which identify the controls and effect of fire on specific taxa. Fire is a complex entity differing in its impact with both intensity and severity, and vegetation burned. It is also liable to be impacted by weather, climate and surrounding environmental changes. Specific study site characteristics are also an important consideration. This chapter highlights the consistent correlation between charcoal and taxa at the majority of study sites, except those within Killarney National Park. It also emphasises that not all fires are equal, in size, magnitude, severity or response. Chapter 7 will examine the impact of fire on biodiversity and attempt to quantify the magnitude of fire necessary to have a significant impact on biodiversity. This study is the first attempt to quantify the effects of both human and natural fire within the Irish landscape across multiple study sites and is expected to be built on in the future.

6.7 Conclusion

This chapter presents a detailed investigation of the relationship between fire and vegetation composition at seven study sites throughout Ireland. Vegetation transitions have been examined in conjunction with climate change, anthropogenic activity and fire occurrence. From the statistical analyses and interpretation a number of significant conclusions can be drawn;

1. The vegetation composition within each of the identified time periods is significantly different, as determined by the pollen, MRPP and ordination analysis.
2. The early Holocene was characterised by rapid climate change and plant immigration, possibly due to increased temperature following the termination of the last glaciation and is demonstrated at numerous sites here with widely spaced samples in the ordination analysis pre 9000BP.
3. Fire events tend to be clustered together within the ordination plots suggesting that fire events were occurring within similar time periods or under similar vegetation and climate conditions.
4. At a number of sites the present day was deemed similar to the early Holocene between 10,000 and 13,000BP, suggesting that the present day is experiencing a similar vegetation composition.
5. Fire events are also seen to be represented close to the present day at a number of sites within the ordination plot, indicating that fire events are possibly increasing towards the present or are occurring under similar environmental conditions.
6. The highest periods of change and instability identified throughout the Holocene are generally seen to be associated with the identified fire events at each site.
7. A consistent taxa-charcoal correlation was identified at the majority of sites except those within Killarney National Park, which may be due to differing climatic or site specific conditions.

8. Specific species can be designated as fire adapted (*Quercus, Pinus* and *Poaceae*), fire dependent (*Corylus, Alnus, Pinus* and *Salix*), fire resistant (*Betula, Quercus, Pinus,* Poaceae and *Calluna*) and fire sensitive (*Ulmus*).

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Chapter 7

Examining Biodiversity and its interaction with fire throughout the Holocene in Ireland

Abstract

Wildfires have been increasing in Ireland in recent years and there are many opportunities for fire to enhance or adversely affect biodiversity. Climate change has been the catalyst to focus discussions on biodiversity conservation and management, with the increase in extreme events such as fires contributing to habitat degradation, species loss and an overall decrease in biodiversity, putting ecosystems in an increasingly vulnerable position. This chapter examines changes in biodiversity throughout the Holocene at seven study sites in a range of locations throughout Ireland; in an attempt to understand the causal relationship between anthropogenic and environmental factors. It also uses specific fire events identified at each study site to investigate the impact that fire may have on biodiversity, and what magnitude of fire is necessary to have a significant impact. A number of diversity indices are used to reconstruct biodiversity throughout the Holocene, and statistical techniques are applied to test the relationship between these biodiversity indices and fire events. Major conclusions can be drawn that suggest fire is significantly impacting biodiversity across all of the sites, and specifically with fires of a higher magnitude are having an increasingly negative impact on biodiversity. Patterns of biodiversity are also observed that suggest they closely follow climate oscillations, and are intrinsically linked to a number of anthropogenic and environmental factors at play at each study site.

7.1 Introduction

In recent years biodiversity has come to the forefront of many climate change discussions, with the main efforts focused on how to reduce biodiversity loss (Secretariat of the Convention on Biological Diversity (2010) Global Biodiversity Outlook 3). Ecosystems are already showing negative impacts under current levels of climate change. Future projections expect increasingly significant impacts on biodiversity, with warming temperatures, more extreme weather, and changing patterns of rainfall and drought all important influencing factors (Bellard et al., 2012). Currently there is abundant evidence that climate change impacts biodiversity and it is likely to become one of the most significant drivers of biodiversity loss by the end of the century, through extinctions, habitat degradation, overexploitation, fragmentation and destruction (McMahon et al., 2011, Beaumont et al., 2011, Dillon et al., 2010). Climate change is already forcing biodiversity to adapt either through shifting habitat, changing life cycles, or the development of new physical traits (Botkin et al., 2007). Conserving natural terrestrial, freshwater and marine ecosystems and restoring degraded ecosystems is essential for future sustainability. Ecosystems are essential to the global carbon cycle and in adapting to climate change, they provide a wide range of ecosystem services that are essential for human and environmental well-being. Maintaining and restoring biodiversity through conservation and management can help to reduce some of the negative impacts from climatic changes, however it is important to recognise that with an increase in the rate and magnitude of climate change, natural adaptations will become increasingly difficult (Schmitz et al., 2003). A number of strategies to help reduce biodiversity loss include designating specific conservation areas and putting sustainable management strategies in place, and reducing stressors on ecosystems such as

pollution, exploitation, habitat loss and the spread of invasive species will help reduce biodiversity loss (Heller and Zavaleta, 2009). The management of biodiversity is complex and requires the involvement of many different parties, including government organisations, private companies, NGO's and volunteers. Following on from this national and international commitment, legislation and enforcement is important, and offers an essential framework to help promote sustainable biodiversity (Visconti et al., 2015)

The term 'biodiversity' emerged as a contraction of 'biological diversity' and was first proposed by Walter G. Rosen during the planning of the 1986 National Forum on Biodiversity (Hawksworth, 1995). A variety of definitions exist to describe 'Biodiversity', however for the purposes of this chapter biodiversity will be discussed in the terms of the variety and abundance of species in a defined unit of study. It is synonymous with species richness, evenness and relative species abundance in space and time (Hubbell, 2001), and spans a range of organizational levels e.g. genetic, organismal and ecological. Measures of biodiversity are therefore useful in monitoring changes in the abundance and composition of species through time. By monitoring long term changes in biodiversity it is possible to potentially identify human and climate impacts on the environment (Froyd and Willis, 2008).

The measurement of biodiversity is based on three assumptions (Preet 1974). Firstly that all species are equal, species of conservation importance or species that make a disproportionate contribution to community function do not receive special weighting. The second assumption is that all individuals are equal, there is no distinction between for example a large tree and a small seedling. The final assumption is that species abundance has been recorded using appropriate and comparable units (Magurran, 2013). In this chapter the abundance of species is measured in terms of the number of individuals, represented by pollen count data.

A wide variety of indices exist to try and quantify different aspects of biodiversity, such as richness, evenness and abundance (Gotelli and Colwell, 2001). No index exists which encompasses all of these components, therefore ecologists have strived to create increasingly superior measures of diversity over the years. It has therefore become increasingly difficult to select the most appropriate diversity measure due to the plethora of indices available (Molinari, 1996). A number of important factors should be taken into consideration when choosing a diversity measure; firstly select which aspect of biodiversity is being investigated, select an adequate sample size to meet the objectives and finally consider replication, to ensure statistical analysis is possible (Magurran, 2013). Ideally a study should be designed prior to data collection to ensure that all aspects meet the appropriate requirements. Biodiversity is used principally for comparisons i.e. is one community more diverse than another, or was a point in the past more diverse than today. Biodiversity is largely bound by environmental factors, such as climate conditions, soil type and water supply, and is therefore related to the geography of an area. Diversity indices provide information about the composition of a community, species rarity and frequency within a population. These indices are important tools used to understand community structure. Diversity is most commonly used to determine the stability of an environment, to monitor if it is degrading or improving, and is a useful measure to compare two or more environments eliminating the need for extensive lists of species (Magurran, 2013).

Biodiversity can be examined over time with a palaeoecological perspective. Changes in Quaternary environments are directly applicable to on-going issues of global conservation (Froyd and Willis, 2008). Such studies provide a wealth of information which is relevant to conservationists, land managers and policy makers. Palaeoecological techniques produce multi-proxy records which are important archives of past environmental change (Willis and Birks, 2006). These abrupt

changes and their influencing factors can be examined to increase understanding about processes and interactions, and possibly guard against negative impacts in the future. Types of proxies available include pollen counts to provide a vegetation reconstruction, and charcoal counts to reconstruct past fire regimes. This chapter utilises such data sets to examine how biodiversity changes over time at a number of study sites, and how this biodiversity is affected by past fire events. Shackelford et al. (2015) carried out a study examining a correlation between species loss and fire history, but failed to identify any strong correlation between the two. In a similar analysis Gosper et al. (2012) found that plant species diversity peaks immediately after a fire, before decreasing for a short period and then maintaining a steady state throughout fire free periods. Although prescribed burning was promoted for increasing biodiversity (Fries et al., 1997) and a low-intensity fire regime previously adopted in Scots pine forests (Froyd and Willis, 2008), it was evident on further examination of palaeoecological studies that prescribed burning may actually be detrimental to the biological diversity it was designed to maintain (Bradshaw and Hannon, 1992, Ohlson and Tryterud, 1999, Niklasson and Drakenberg, 2001). A decline in species richness was also observed where woody species invaded due to altered fire frequencies, which caused a shift in soil nutrients and plant biomass (Stephens et al., 2009).

Fire has been used worldwide as a management tool for biodiversity conservation, and Kelly et al. (2014) aims to identify the optimal balance of fire management strategies to prevent biodiversity loss. Total fire suppression will ultimately result in an inevitable biodiversity loss through larger and more intense fire, while frequent burning may also be inappropriate and adversely impact biodiversity. It is therefore important to further study the interaction between fire and biodiversity, in a range of contexts using a variety of methods, so an appropriate consensus of management may be reached. There is a lack of knowledge of how

biodiversity changes throughout the palaeo-record within Ireland and how it is impacted by fire.

This chapter utilises pollen count records from seven study sites throughout Ireland, to examine and compare the biodiversity via a number of appropriate and standard diversity indices. The records extend from the present day back throughout the Holocene to provide a palaeoecological perspective on biodiversity. To examine how fire interacts with biodiversity, specific fire events were examined and how diversity changes before and after these events.

7.2 Aims

1. Examine the biodiversity at each of the study sites using a variety of indices.

2. Identify how biodiversity varies over time and between study sites.

3. Examine the relationship between identified fire events and biodiversity.

7.3 Study Sites

All seven study sites (discussed in detail in Chapter 3) are included in this analysis examining the interaction between fire and biodiversity. Pollen count data identified in Chapter 6 are utilised here to calculate the biodiversity measures. Charcoal and fire events discussed here are as determined in Chapter 4.

7.4 Methodology

To generate the macro-charcoal data presented, charcoal analysis was carried out on the sediment cores from all sites and the method for preparation is adapted from those described by Mooney and Black (2003) and Mooney and Radford (2001). Digital image analysis using Image J was applied once the samples were prepared, to generate count and area data, and follows methods similar to Schlachter (2012). Fire Events and their magnitude were identified via the CharAnalysis programme (Higuera, 2009). Each of the sediment cores was also radiocarbon dated, and a robust chronology was produced using BChron and Intcal13 calibration curve (Haslett and Parnell, 2008). The chronologies for each study site can be seen in the Appendix. The vegetation composition at each site was determined via standard pollen analysis using methods adapted from Shackley (1981) and is outlined in Paleoethnobotany: A handbook of Procedures (Pearsall, 1989). The pollen from Cuckoo Lough was counted and identified using the reference collection at Trinity College Dublin. Pollen data for the remaining study sites is available from previous projects, details are outlined in Table 2.1 Chapter 2. The pollen data sets were screened and adjusted to reflect common nomenclature, which follows Moore and Webb (1991). Pollen counts rather than percentages are used here for estimates of Biodiversity. Archaeological time periods are used here to define periods within the Holocene and are outlined in Table 5.1 Chapter 5.

7.4.1 Measuring Biodiversity

To assess different aspects of biodiversity at each of the study sites a number of parameters discussed below were calculated utilising pollen

count data and statistical analysis in R. The pollen data used includes tree, shrub, herb, and pteridophyte taxa, excluding aquatics and unidentified grains. The taxa were not amalgamated into families and were defined to species level where possible. A common pollen nomenclature was used.

Rank/Abundance Plot (Whittaker Plot)

One of the most informative methods of displaying species abundance is to use a rank/abundance plot (Magurran, 2007). Species are plotted in sequence from most abundant to least abundant along the horizontal (x) axis, with abundance displayed in log10 format on the vertical (y) axis. These plots can clearly display contrasting patterns of species richness and highlight differences in evenness among assemblages. The shape of a rank/abundance plot can also inform which species abundance model best describes the data i.e. a geometric, log normal or broken stick model. A rank abundance plot was produced for each of the study sites comparing the different archaeological time periods, as well as a plot comparing all of the study sites. This was carried out within the BiodiversityR package in R (Kindt and Coe, 2005). Finally the rank abundance distributions are compared between sites using a K-S Test.

Shannon Index

Shannon's Index is a measure of diversity that accounts for both abundance and evenness of the species present (Magurran 2013). It assumes that individuals are randomly sampled from an infinitely large community, and that all species are represented in the sample. Typical values lie between 1.5 and 3.5 in most ecological studies, and the index is rarely greater than 4. The Shannon index increases as both the richness

and the evenness of the community increase. The Shannon Index is produced by calculating the proportion of species (i) relative to the total number of species (p_i), and multiplying this by the natural logarithm of this proportion ($\ln p_i$). The resulting value is summed across species and multiplied by -1:

$$H = -\sum_{i=1}^{S} p_i \ln p_i$$

The overall Shannon Index was calculated at each of the study sites, as well as the index at each of the pollen depths. A t-test was then used to compare the Shannon index between study sites and between archaeological time periods.

Simpson's Index

The Simpson Index is a measure of dominance and displays the variance of the species abundance distribution (Magurran 2013). It is weighted towards the most abundant species in the sample and is less sensitive to species richness. This is in contrast to the Shannon Index which is weighted towards the more rare species. Simpson's Index is expressed by:

$$D = \frac{1}{\sum_{i=1}^{S} p_i^2}$$

The Simpson's Index was calculated for each of the study sites and at each pollen depth. Similarly the indices were compared using a t test and the results are presented in Table 7.1. Simpson's and Shannon indexes were both calculated here to test the variability in their reconstructions of diversity.

Evenness Measure

Pielou's evenness measure was calculated for each pollen depth at each of the study sites. It is calculated by:

J=H/ln(S) where H is the Shannon Index and S is total number of species.

The evenness typically ranges from 0 to 1, with 1 representing complete evenness of species. As the evenness of a community approaches 1 the variation in the number of species decreases (Heip, 1998). This evenness was compared to a separate measure of evenness calculated by dividing the reciprocal form of the Simpson Index by the number of species in the sample:

$$E_p = \frac{D}{D_{max}} = \frac{1}{\sum_{i=1}^{s} p_i^2} \times \frac{1}{S}$$

This measure of evenness is the Simpson's evenness and ranges from 0 to 1 and is not sensitive to species richness (Smith and Wilson, 1996). The evenness was calculated for each of the study sites.

Log Series Model and Fishers Alpha

This logarithmic model attempts to describe mathematically the relationship between the number of species and the number of individuals within those species. The model is straight forward to fit and it's α parameter has proved to be an informative and robust diversity measure. This is a parametric index of diversity that assumes that the abundance of species follows the log series distribution:

$$\alpha x, \frac{\alpha x^2}{2}, \frac{\alpha x^3}{3}, \ldots\ldots \frac{\alpha x^n}{n}$$

where each term gives the number of species predicted to have 1,2,3,....n individuals in the sample. The estimation is made only for genuine counts of individuals. The α and n parameters summarize the distribution and are related by:

$$S=a*\ln(1+n/a)$$

where *S* is number of taxa, *n* is number of individuals and *a* is the Fisher's alpha. This is a robust measure which can be used even when the data do not conform to a log series distribution (Magurran, 2013). Hayek and Buzas (1997) believe it to be a useful index provided the ratio of the total number of individuals to the species number (N/S) exceeds 1.44, which is the case for all the study sites here. In many situations, alpha is approximately equal to the number of species represented by a single individual. The value of alpha is independent of sample size when the number of individuals in the sample exceeds 1000 (Taylor et al., 1979). The α parameter was calculated for each of the study sites using the 'vegan' package in R. Figure 7.5 shows the plot of the Fisher fit model to the data from each study site.

Rarity

Rarity, defined by Gaston (1994) is the species that fall in the lower quartile of the species abundance distribution. Likewise the upper quartile can identify common species. This measure is relevant to biodiversity and will depend on the scale of the investigation, but it provides a simple and comparable measure of rarity. For each of the study sites in this chapter the taxa were plotted against the log of the total number of each taxa. This can be seen in Figure 7.5 with the upper

and lower lines representing the Gaston rarity quartiles. The rarity of species was compared between study sites using a K-S test and the results are presented in Table 7.3.

Rarefied Species Richness

A common problem in comparing species richness indices is the difference in sample size. Rarefaction is a technique that reduces the sample data to a common level of abundance, therefore direct comparisons of species richness can be made (Rossi, 2011). This analysis was carried out in R using the vegan package. The information provided by each of the study sites is used to estimate the richness of a smaller uniform sample, and the rarefied species richness was calculated for each sample depth at each of the study sites. Rarefaction curves showing the average number of individuals in each archaeological period were plotted for each study site and can be seen in Figure 9.2 in the Appendix. A comparison of rarefied species richness between study sites and between archaeological periods was then examined via an ANOVA analysis in R and Tukey's post-hoc test. Results of these analyses can be seen in Table 7.4.

7.4.2 Biodiversity and Fire

To analyse if biodiversity is affected by fire, the rarefied richness before and after each fire event was compared in a 200 year time window. The data from each study site were composited and a paired t-test carried out in R under the null hypothesis of equality of averages. The diversity index of rarefied richness was chosen because it is the most comparable having been rarefied to a common sample size between study sites. A 200 year time window before and after each fire event was chosen based on the nature of the sample intervals available and to utilise an adequate

number of indices within each window. The results from this t-test can be seen in Table 7.5. To examine the magnitude of fire event necessary to have an impact on biodiversity, a similar analysis was applied. Fire events exceeding magnitudes of 30, 50, 100 and 400 pieces $cm^{-2}peak^{-1}$ were selected, as these are common magnitudes observed, and the rarefied richness before and after each of these events was composited from each study site. A paired t-test was then carried out between the data sets at each of these magnitudes. The results of this analysis can be seen in Table 7.5.

To further examine the impact of fire on biodiversity, the largest fire event was selected from each study site and the rarefied richness before and after the event was compared. Finally to visually illustrate how biodiversity varies in response to fire events, Simpson's and Shannon's index were plotted against time, with the identified fire events from each study site.

7.5 Results

7.5.1 Measuring Biodiversity

Rank/Abundance Plot (Whittaker Plot)

A Rank/Abundance plot was created to compare the diversity at each of the seven study sites, with species rank on the horizontal axis and abundance on the vertical axis. In this case the logarithm of the abundance was plotted on the vertical axis to account for a small number of taxa being highly dominant, and allows taxa whose abundances span several orders of magnitude to be accommodated on the same graph. Figure 7.1 overleaf shows the comparison of rank/abundance between each of the study sites. Each of the study sites show a relatively similar distribution of abundance.

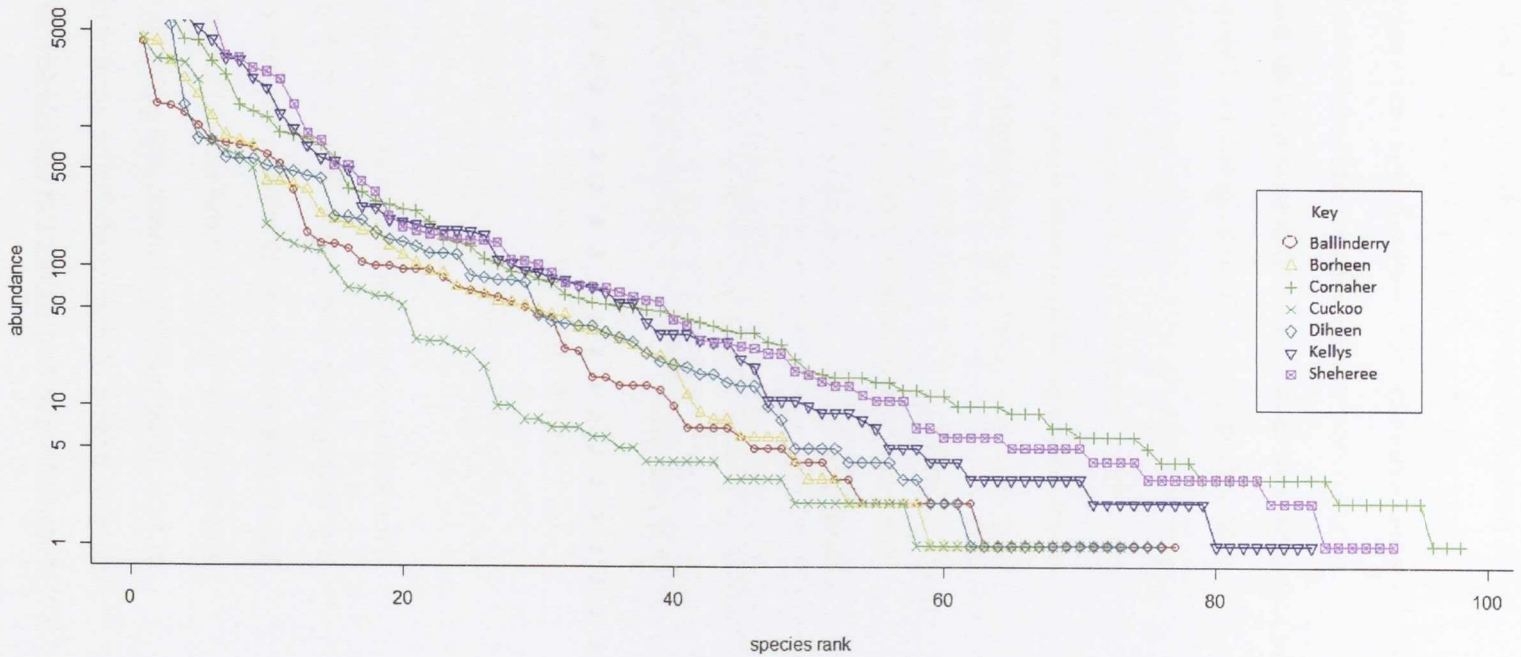


Figure 7.1 Comparison plot of Rank/Abundance for each site.

The species richness of each site is high, represented by the width of the curve on the horizontal axis. Ballinderry and Cuckoo Lough show a slightly lower species richness than the other sites, with Sheheree and Cornaher Lough having two of the highest levels of species richness. The steepness of the rank/abundance curve is an indication of evenness i.e. how similar species are in abundance. Cuckoo Lough displays the least amount of evenness with the steepest rank/abundance curve. Two sites with some of the highest level of evenness are Ballinderry and Cornaher Lough. A completely evenly distributed system would be represented by a horizontal straight line. A number of models were fitted to the rank/abundance curves from each of the study sites in an attempt to describe the underlying biological characteristics of the data. It is important however to remember that just because the species abundance relationship is in line with one specific model, does not mean that it adheres to the underlying model assumptions. If the data fit a particular model or perhaps a number of models well, then they must be accepted pending additional investigation. The abundance curves and model fits can be seen in Figure 7.2. A number of the study sites appear to fit similar models; Borheen, Diheen and Kelly's Lough can be described by the Zipf-Mandelbrot model, which has been interpreted as reflecting a successional process where later colonists have more specific requirements and are therefore rarer than the first species to arrive (Frontier, 1985). Cuckoo and Sheheree Lough appear to fit well with the Preemption model. This model is similar to the geometric series model and describes communities with uneven species abundance distributions and low diversity characterised by a few dominant species. After colonisation each new species gives rise to niche preemption and a sequential colonisation of species into a community occurs. Finally Ballinderry and Cornaher Lough fit well with the Log normal and Zipf models respectively. The log normal model is one of the most common and usually fits large mature communities.

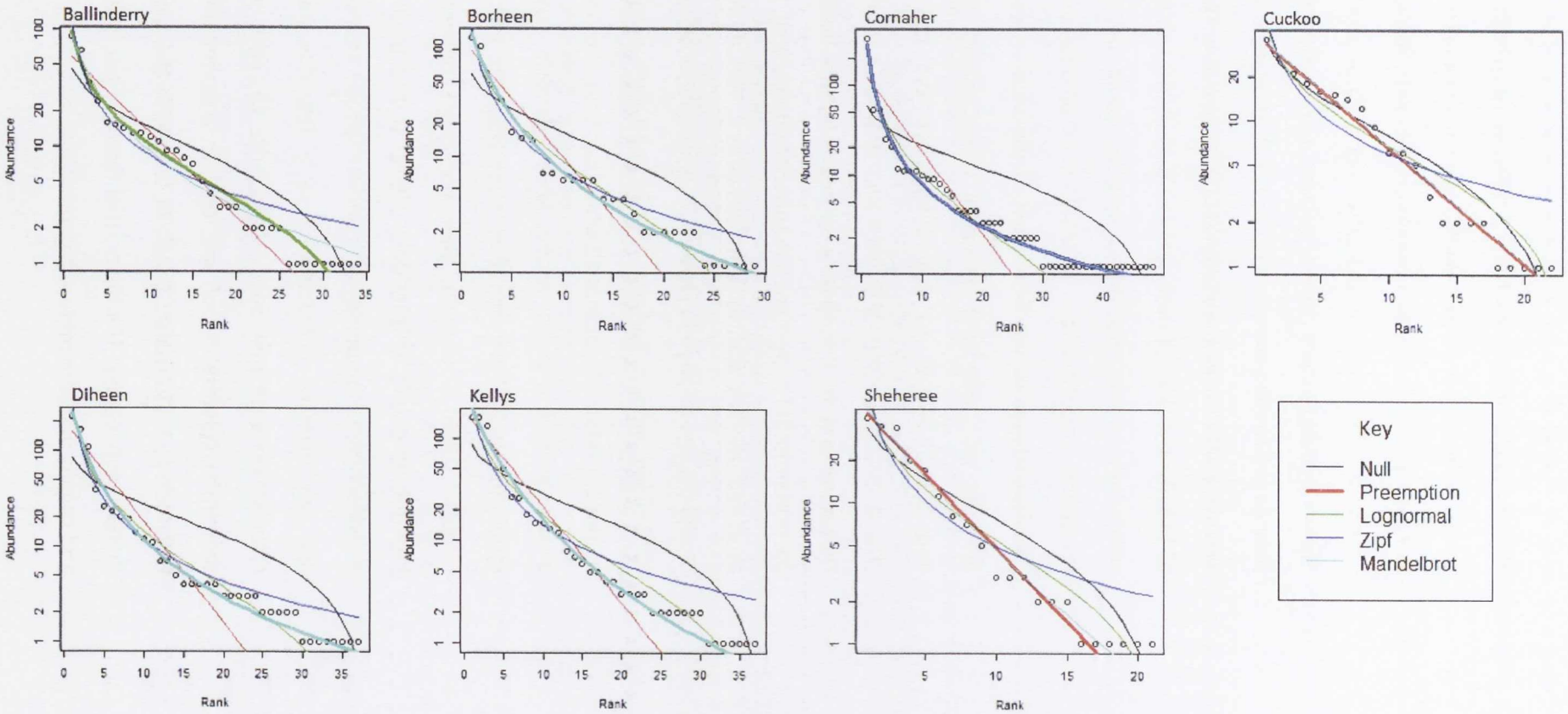


Figure 7.2 Model fits to the Rank/Abundance data at each study site.

Each species that arrives splits the niche space and occupies a space proportional to its relative abundance (Sugihara, 1980). Zipf models are closely related to the Zipf-Mandelbrot model, and the presence of a species is dependent on previous physical conditions and previous species presences. Pioneer species therefore require few prior conditions and late successional species require more conditions and are thus rarer. The interpretations from the literature described here are based on spatial interpretation, but are also considered valid for temporal analyses (Magurran 2013). The models fitted here appear to relate to the study sites in terms of location, with distinct models characterising the upland and lowland sites.

To compare differences in abundance, evenness and richness between archaeological periods, a rank/abundance curve was created for each time period at each of the study sites. These plots can be seen in Figure 7.3 Each study site shows a varying rank abundance plot for each archaeological period; for example at Ballinderry Lough the Palaeolithic period represents the lowest species richness and a low evenness, whereas at Borheen Lough the same period represents one of the highest species richness and evenness periods. There are correlations between sites, such as the Medieval period which shows similar characteristics of evenness, richness and abundance at Cornaher, Cuckoo, Kelly's and Sheheree Lough.

Shannon Index

The Shannon Index was calculated for each of the study sites using the 'vegan' package in R. The study sites were then compared using a t-test between sites and between archaeological periods. The results from this test can be seen in Table 7.1 A comparison between study sites has illustrated that there are two instances where three comparisons were deemed similar and produced a p-value greater than 0.05. These

comparisons were between, Borheen and Diheen Lough, Borheen and Kelly's Lough and Cornaher and Cuckoo Lough. Looking at the t-test results comparing the different archaeological periods presented in Table 7.2 There is a wide variety of periods considered statistically similar at each of the study sites. Borheen Lough and Kelly's Lough show similar patterns, with comparisons in the Palaeolithic, Neolithic and Medieval time periods considered statistically similar with a p-value greater than 0.05. Cuckoo Lough and Sheheree Lough also have significant comparisons in common between the Bronze Age and Iron Age and Modern periods and between the Iron Age and Modern period. The most common comparison significant across 5 of the study sites, Borheen, Cornaher, Cuckoo and Kelly's Lough, is between the Medieval and Modern time periods.

Simpsons Index

The Simpson's index was calculated for each pollen depth at each of the study sites, and is a measure of dominance displaying the variance of the species abundance distribution. To compare the index between sites a t-test was calculated in R. Table 7.1 shows significant results between the study site comparisons and archaeological periods. Kelly's Lough was identified as statistically similar to Borheen and Cuckoo Lough, while Borheen Lough was also identified as being similar to Cornaher, Cuckoo and Diheen Lough. Looking at the comparisons between archaeological periods (Table 7.2) there is a wide range of significant comparisons which vary depending on study site. One of the most common relationships is the similarity between the Medieval and Modern time periods which occurs at each study site except Ballinderry Lough. The relationship between the Iron Age and Medieval, and Iron Age and Modern periods is also significant at a range of sites including Ballinderry, Borheen, Cornaher and Cuckoo Lough.

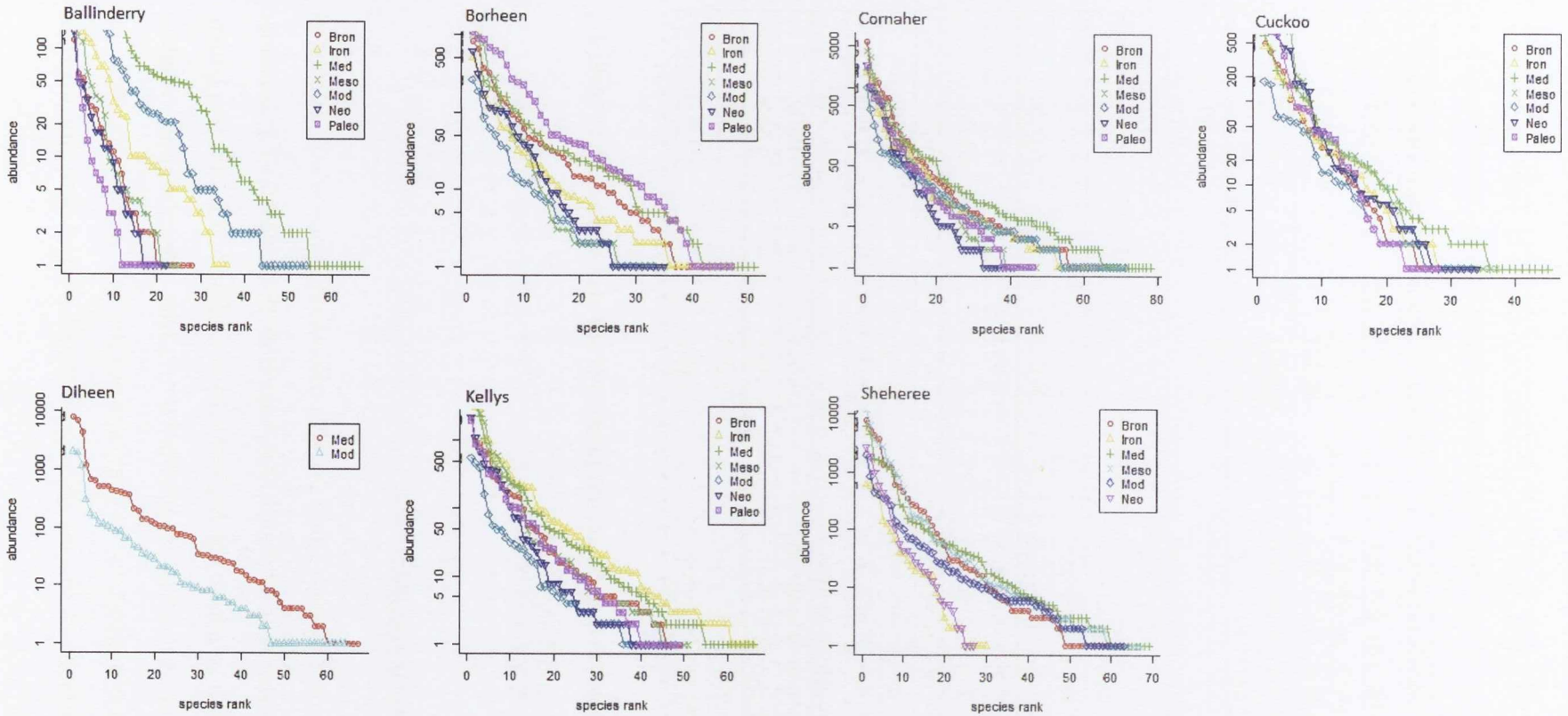


Figure 7.3 Rank/Abundance plots for each archaeological time period at each study site.

Table 7.1 T-test results for Shannon and Simpson's diversity indices (statistically similar results in red)

Study Site Comparison	Simpson's Index	Shannon Index
Ballinderry vs Borheen	<0.001	<0.001
Ballinderry vs Cornaher	<0.001	<0.001
Ballinderry vs Cuckoo	<0.001	<0.001
Ballinderry vs Diheen	<0.001	<0.001
Ballinderry vs Kellys	<0.001	<0.001
Ballinderry vs Sheheree	<0.001	<0.001
Borheen vs Cornaher	0.077	0.02
Borheen vs Cuckoo	0.188	0.01
Borheen vs Diheen	0.729	0.09
Borheen vs Kellys	0.229	0.65
Borheen vs Sheheree	0.007	<0.001
Cornaher vs Cuckoo	<0.001	0.78
Cornaher vs Diheen	0.052	<0.001
Cornaher vs Kellys	0.001	0.002
Cornaher vs Sheheree	0.487	0.033
Cuckoo vs Diheen	0.021	<0.001
Cuckoo vs Kellys	0.868	<0.001
Cuckoo vs Sheheree	<0.001	0.002
Diheen vs Kellys	0.027	0.117
Diheen vs Sheheree	<0.001	<0.001
Kellys vs Sheheree	<0.001	<0.001

The Palaeolithic period and comparisons are also important at Borheen, Cornaher and Kelly's Lough.

Evenness Measure

The evenness of each study site was calculated using Pielou's Evenness. The evenness values for each site range from the lowest 0.63 at Cornaher and Diheen Lough, to the highest 0.74 at Cuckoo and Ballinderry Lough. The evenness typically ranges from 0 to 1, with 1 representing complete evenness of species. As the evenness of a site approaches 1 the variation in the number of species decreases. When plotted with the Shannon

index against time, Pielou's evenness follows a very similar distribution at each of the study sites. Looking at the average values of evenness for each site, Cuckoo and Ballinderry Lough show similar levels of evenness, as do Borheen, Kelly's and Sheheree Lough with values around 0.65. Simpson's evenness measure was also calculated as a comparison, and produced similar patterns of evenness between the study sites. With the lowest evenness at Diheen and Cornaher Lough, with values of 0.16 and 0.20 respectively, and the highest evenness at Cuckoo Lough with a value of 0.37. When plotted the distribution of evenness follows a very similar pattern to that of the Simpson's Index and Simpson's Reciprocal.

Log Series Model and Fishers Alpha

The log series model was fitted to the diversity data from each of the study sites using the 'vegan' package in R. These plots can be seen in Figure 7.4. This figure shows that the model fits each of the study sites reasonably well. From this model the alpha parameter was calculated and is a robust diversity measure as it can be used even when the data do not fit the model particularly well. The estimates of the alpha parameter range from the lowest at Borheen Lough with a value of 234.13 to the highest at Sheheree Lough with a value of 687.41. Cornaher and Kelly's Lough have similar alpha values with 469.1 and 589.1 respectively. The lowest alpha value at Borheen Lough, 234.1 is comparable with that at Ballinderry Lough with a value of 291.4. While the value 399 at Cuckoo Lough is closest to an alpha value of 379.8 at Diheen Lough. The alpha value is approximately equal to the overall number of individuals represented by taxa in a single sample, therefore the sites with a larger alpha value here have a higher level of diversity.

Table 7.2 T-test results for Shannon and Simpson indices per study site and archaeological period.

Study Sites	Ballinderry		Borheen		Cornaher		Cuckoo		Diheen		Kellys		Sheheree	
Archaeological Period	Shannon	Simpson	Shannon	Simpson	Shannon	Simpson	Shannon	Simpson	Shannon	Simpson	Shannon	Simpson	Shannon	Simpson
Paleolithic-Mesolithic	-	-	0.243	0.75	<0.001	0.005	<0.001	<0.001	-	-	0.272	0.268	-	-
Paleolithic-Neolithic	-	-	0.883	0.86	0.288	0.602	<0.001	<0.001	-	-	0.420	0.561	-	-
Paleolithic-Bronze Age	-	-	0.006	0.01	0.809	0.273	<0.001	<0.001	-	-	0.072	0.105	-	-
Paleolithic-Iron Age	-	-	0.022	0.19	0.008	0.114	<0.001	<0.001	-	-	0.027	0.037	-	-
Paleolithic-Medieval	-	-	0.047	0.66	0.002	0.025	<0.001	<0.001	-	-	0.147	0.318	-	-
Paleolithic-Modern	-	-	0.079	0.35	<0.001	0.049	<0.001	0.012	-	-	0.252	0.574	-	-
Mesolithic-Neolithic	NA	NA	0.116	0.78	<0.001	0.001	0.004	0.001	-	-	<0.001	<0.001	<0.001	0.009
Mesolithic-Bronze Age	NA	NA	<0.001	<0.001	<0.001	<0.001	0.096	0.664	-	-	<0.001	<0.001	<0.001	<0.001
Mesolithic-Iron Age	0.288	0.22	<0.001	0.01	<0.001	<0.001	<0.001	0.215	-	-	<0.001	<0.001	<0.001	<0.001
Mesolithic-Medieval	0.240	0.16	<0.001	0.22	<0.001	<0.001	<0.001	0.037	-	-	<0.001	<0.001	<0.001	<0.001
Mesolithic-Modern	0.278	0.25	<0.001	0.04	<0.001	0.003	0.039	0.329	-	-	<0.001	<0.001	<0.001	<0.001
Neolithic-Bronze Age	NA	NA	0.006	<0.001	0.208	0.435	0.570	0.297	-	-	0.002	0.009	<0.001	<0.001
Neolithic-Iron Age	NA	NA	0.022	0.03	<0.001	0.016	0.009	0.408	-	-	<0.001	<0.001	0.002	0.007
Neolithic-Medieval	NA	NA	0.005	0.31	<0.001	0.002	<0.001	0.328	-	-	0.011	0.193	<0.001	0.030
Neolithic-Modern	NA	NA	0.034	0.08	<0.001	0.02	0.087	0.766	-	-	0.157	0.914	<0.001	0.045
Bronze Age-Iron Age	NA	NA	0.009	0.02	<0.001	0.003	0.195	0.682	-	-	0.068	0.124	0.423	0.315
Bronze Age-Medieval	NA	NA	0.053	<0.001	<0.001	<0.001	0.023	0.133	-	-	0.156	0.054	0.023	<0.001
Bronze Age-Modern	NA	NA	<0.001	0.01	0.002	0.018	0.143	0.449	-	-	0.016	0.004	0.689	<0.001
Iron Age-Medieval	0.003	0.06	0.504	0.16	0.478	0.394	0.146	0.178	-	-	<0.001	<0.001	0.045	0.009
Iron Age-Modern	0.518	0.57	0.064	0.38	0.031	0.416	0.454	0.564	-	-	<0.001	<0.001	0.620	0.009
Medieval-Modern	0.014	0.005	0.382	0.43	0.079	0.924	0.908	0.793	0.008	0.007	0.129	0.063	0.015	0.934

Significant results represented in red, Sites with insufficient data for analysis marked as NA, No data available marked as -

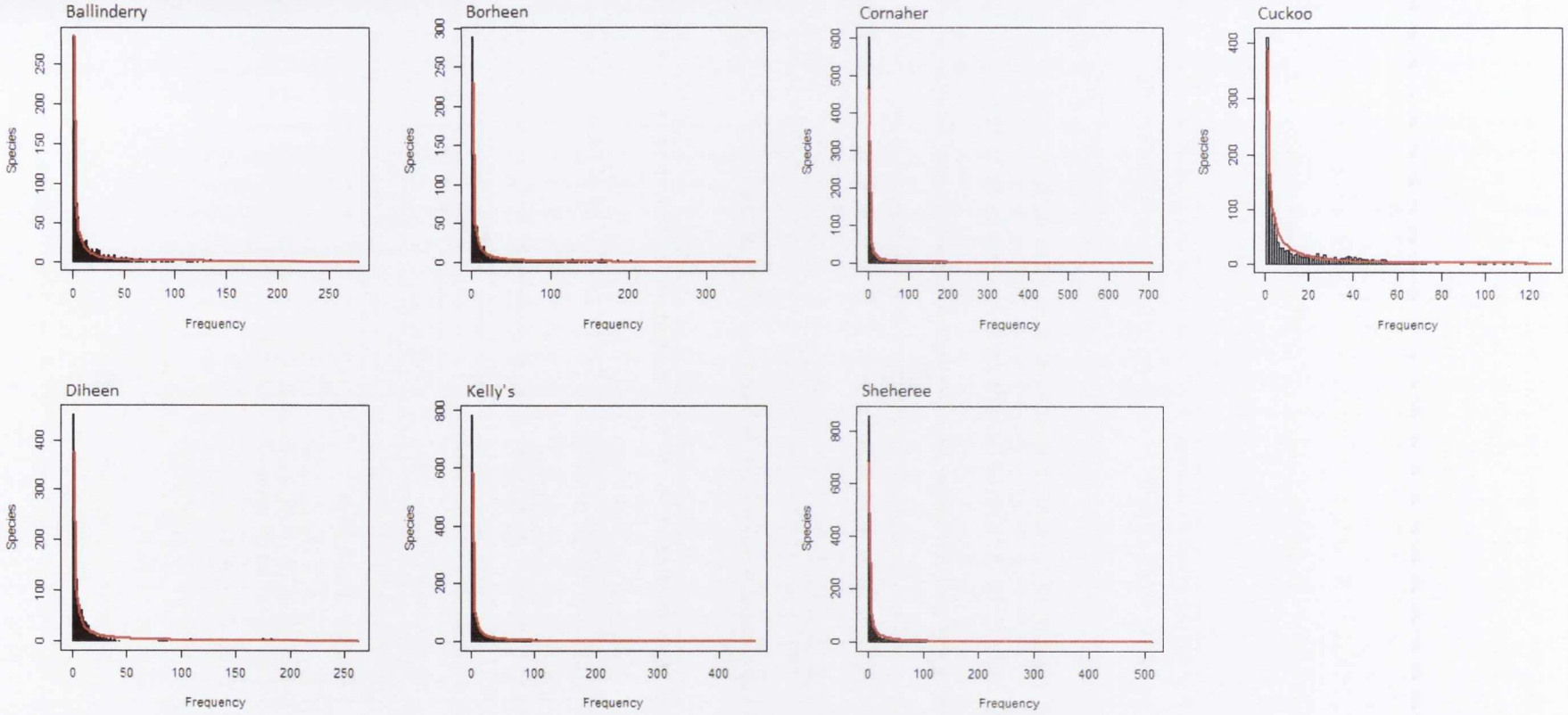


Figure 7.4 Log series model fitted to the diversity data from each study site

Rarity

Rarity plots were produced for each study site with the upper and lower quartiles encompassing most abundant and rarest species respectively. Figure 7.5 shows the rarity plots for each site with each taxon plotted against the log of the total number of that taxon. The rarity of species was compared between study sites using a K-S test and the results are presented in Table 7.3. The results indicate that all comparisons are statistically similar except those involving Cuckoo Lough. This indicates that the rare species represented at Cuckoo Lough are significantly different than those recorded at each of the other study sites. The highest level of comparison was between Ballinderry and three other sites Cornaher, Kelly's and Sheheree Lough with a p-value of 1. Three other comparisons yielded a p-value of 1, between Cornaher and Kellys Lough, Cornaher and Sheheree Lough and Kelly's and Sheheree Lough.

Table 7.3 Significant results from K-S test on rarity of species.

Comparison	P-Value
Ballinderry vs Borheen	0.72
Ballinderry vs Cornaher	1
Ballinderry vs Diheen	0.99
Ballinderry vs Kellys	1
Ballinderry vs Sheheree	1
Borheen vs Cornaher	0.89
Borheen vs Diheen	0.16
Borheen vs Kellys	0.97
Borheen vs Sheheree	0.94
Cornaher vs Diheen	0.93
Cornaher vs Kellys	1
Cornaher vs Sheheree	1
Diheen vs Kellys	0.81
Diheen vs Sheheree	0.88
Kellys vs Sheheree	1

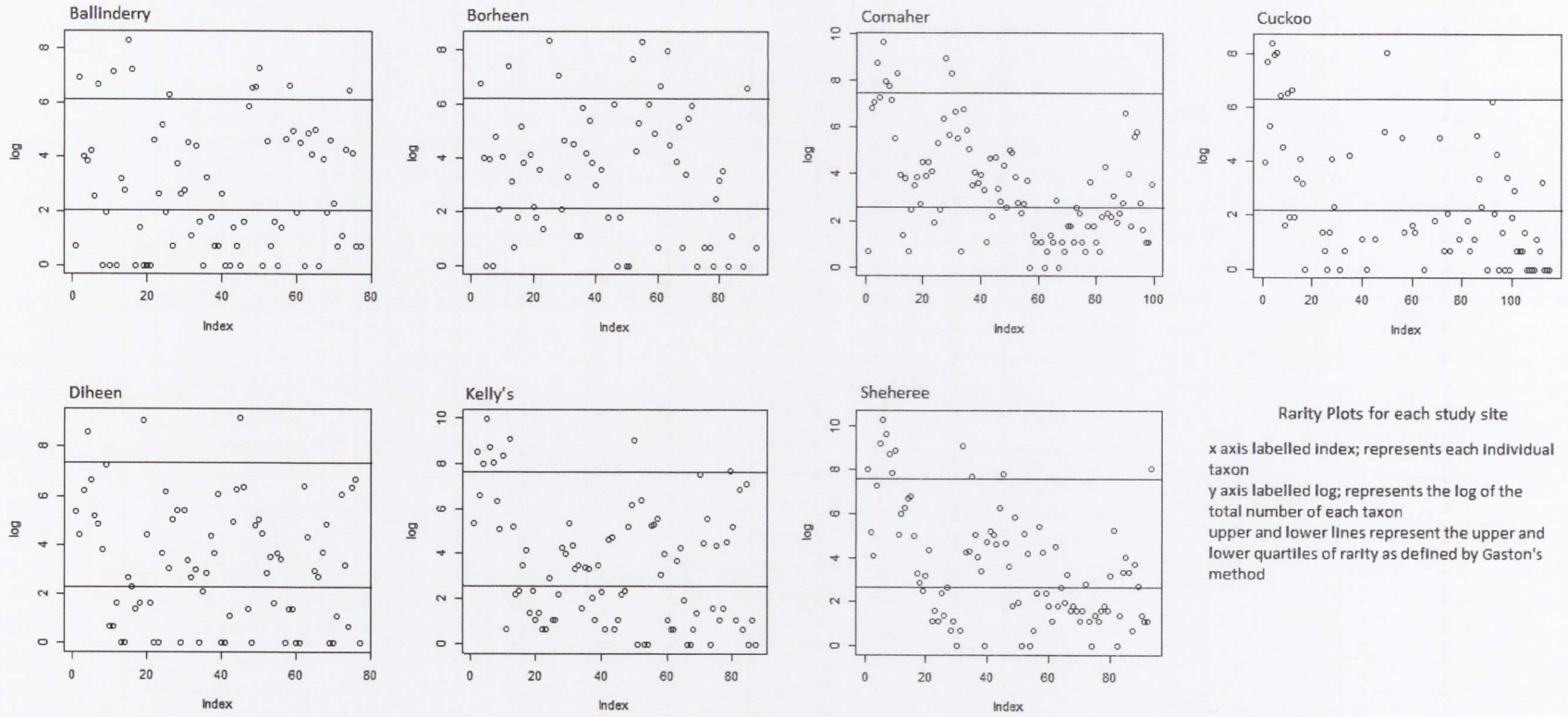


Figure 7.5 Rarity species plots for each study with upper and lower quartiles defined by Gaston's method.

Table 7.4 ANOVA results for Rarefied Richness with factors Site and Archaeological Period.

ANOVA	Df	Sum Sq	Mean Sq	F value	p-value
Site	6	16280	2713.4	187.99	<0.001
Period	6	9145	1524.4	105.59	<0.001
Site:Period	30	2658	88.6	6.14	<0.001
Residuals	534	7708	14.4		

Table 7.5 Tukey's Post Hoc Test Results for Study Site comparisons (statistically different results in red)

Site	Diff	lwr	upr	p adj
Bor-Ball	-0.987	-3.471	1.497	0.903
Cor-Ball	-1.992	-4.104	0.121	0.079
Cuc-Ball	-11.71	-13.787	-9.633	0.000
Dih-Ball	7.034	4.669	9.398	0.000
Kell-Ball	0.568	-1.499	2.636	0.984
Sheh-Ball	-6.725	-8.672	-4.778	0.000
Cor-Bor	-1.005	-3.153	1.143	0.810
Cuc-Bor	-10.72	-12.84	-8.611	0.000
Dih-Bor	8.021	5.625	10.417	0.000
Kell-Bor	1.555	-0.549	3.659	0.304
Sheh-Bor	-5.738	-7.723	-3.753	0.000
Cuc-Cor	-9.719	-11.38	-8.058	0.000
Dih-Cor	9.026	7.017	11.03	0.000
Kell-Cor	2.559	0.911	4.208	0.000
Sheh-Cor	-4.733	-6.228	-3.239	0.000
Dih-Cuc	18.74	16.77	20.715	0.000
Kell-Cuc	12.28	10.68	13.88	0.000
Sheh-Cuc	4.985	3.542	6.429	0.000
Kell-Dih	-6.466	-8.427	-4.505	0.000
Sheh-Dih	-13.76	-15.59	-11.926	0.000
Sheh-Kell	-7.293	-8.723	-5.863	0.000

Table 7.6 Tukey's Post Hoc Test Results for Archaeological Period comparisons (statistically different results in red)

Period	Diff	lwr	Upr	p adj
Iron-Bron	2.851	0.872	4.829	0.000
Med-Bron	1.005	-0.486	0.419	0.419
Meso-Bron	-6.914	-8.462	-5.367	0.000
Mod-Bron	2.679	0.571	4.788	0.004
Neo-Bron	-4.600	-6.567	-2.634	0.000
Palaeo-Bron	-4.817	-6.796	-2.837	0.000
Med-Iron	-1.846	-3.653	-0.039	0.042
Meso-Iron	-9.765	-11.619	-7.911	0.000
Mod-Iron	-0.171	-2.514	2.171	0.999
Neo-Iron	-7.451	-9.667	-5.235	0.000
Palaeo-Iron	-7.668	-9.895	-5.442	0.000
Meso-Med	-7.919	-9.239	-6.599	0.000
Mod-Med	1.674	-0.274	3.623	0.146
Neo-Med	-5.605	-7.399	-3.812	0.000
Palaeo-Med	-5.823	-7.629	-4.016	0.000
Mod-Meso	9.594	7.602	11.586	0.000
Neo-Meso	2.314	0.473	4.155	0.004
Palaeo-Meso	2.097	0.243	3.951	0.015
Neo-Mod	-7.279	-9.612	-4.947	0.000
Palaeo-Mod	-7.497	-9.839	-5.154	0.000
Palaeo-Neo	-0.217	-2.433	1.999	0.999

Rarefied Richness

The rarefied species richness was calculated for each of the study sites using the 'vegan' package in R. Rarefaction curves showing the average number of individuals in each archaeological period were plotted for each study site and can be seen in Figure 9.2 in the appendix. A clear pattern in species diversity can be seen between archaeological periods and study sites; all of the sites follow the general pattern of the highest species richness occurring within the Modern and Medieval periods with the lowest richness generally occurring within the Mesolithic and Palaeolithic. The remaining time periods, Bronze Age, Iron Age and Neolithic, are interspersed between these with a moderate level of species richness. The only site that somewhat violates this pattern is

Borheen Lough, where instead of having the lowest species richness, the Palaeolithic period has one of the highest levels of richness.

A comparison of rarefied species richness between study sites and between archaeological periods was then examined via an ANOVA analysis in R and the results from these analyses can be seen in Table 7.4. The ANOVA table shows that there is an interaction between the two explanatory variables study site and time period with a p-value <0.001. Examining singly the results for study site and period, they also produced a p-value of <0.001 indicating that there is an interaction between the various study sites and between the different archaeological periods.

A Kruskal-Wallis test was also completed to examine if the data from each study site or each archaeological period are statistically different. With regards to study sites the Kruskal-Wallis test produced a p-value <0.001, therefore the null hypothesis of identical distributions can be rejected. Similarly the Kruskal-Wallis test between archaeological periods also produced a p-value <0.001 indicating that the data are statistically different populations. These results represent a comparison between all the study sites and periods as a whole and does not give an insight into individual similarities that may exist.

Therefore to further examine any underlying relationships that may exist a Tukey's post-hoc test was carried out to test where the similarities between the factors from the ANOVA lie. Looking at the results from the study site comparison, there were five instances where the p-value> 0.05 indicating that the two sites were statistically similar. The largest p-values were recorded in comparisons between Kelly's and Ballinderry Lough with a p-value of 0.984, and between Ballinderry and Borheen Lough where a p-value of 0.903 was observed. The comparisons between archaeological periods yielded more results that were statistically similar. Five comparisons between time periods had p-values> 0.05 indicating that the two periods are similar. The Modern and Iron Age

comparison and the Palaeolithic and Neolithic comparison produced the highest p-values of 0.99. Three other comparisons were statistically similar with p-values> 0.05, these were between the Medieval and Bronze Age, Modern and Medieval, and Palaeolithic and Mesolithic.

7.5.2 Biodiversity and Fire

The rarefied richness before and after each fire event was compared using composite data from each study site, and a paired t-test carried out in R. The results from this t-test can be seen in Table 7.5. This t-test produced a p-value of 0.449 suggesting that the null hypothesis of equality of averages should be accepted. This means that there is no significant difference in biodiversity before and after the fire events. The magnitude of fire event necessary to have an impact on biodiversity was examined in a similar analysis. The results of this analysis can be seen in Table 7.7. Fire magnitudes of over 30, 50, 100 and 400 pieces $cm^{-2}peak^{-1}$ were examined. The t-test examining the fire magnitudes associated with these magnitudes all produced p-values larger than 0.05 indicating that there is not a significant effect on biodiversity. However as the magnitude of fire increases the p-value decreases suggesting that fires with a larger magnitude are having an increasing impact on biodiversity.

Table 7.7 T-test results examining richness before and after fire events.

T-test	t	Degrees of freedom	p-value
All Fire Events	-0.76	192	0.449
Events>30 magnitude	0.05	12	0.963
Events>50 magnitude	0.50	7	0.629
Events>100 magnitude	0.81	5	0.455
Events>400 magnitude	1.14	2	0.372

The largest fire event from each study site was then selected and the rarefied richness before and after the event was compared in a 500 year time window. Two study sites Sheheree and Borheen Lough produced p-values less than 0.05 indicating that biodiversity was being impacted by fire. The lack of response at the other study sites is likely to be due to a lack of data as only 1 event is being analysed here and the number of samples in the t-test vary due to inconsistencies in their chronologies.

The t-test above, identified that fires with a larger magnitude have an increasingly small p-value, suggesting that the impact on biodiversity is increasing; to visually illustrate this impact fire events larger than 100 pieces $cm^{-2}peak^{-1}$ were plotted with the Shannon and Simpson's index over time. These events occurred at three of the study sites, Ballinderry, Cornaher and Sheheree Lough. The rest of the study sites contained fire events with a magnitude less than 100 pieces $cm^{-2}peak^{-1}$, and can be seen plotted with the Shannon and Simpson's indices in Figure 9.3 in the appendix.

Ballinderry Lough

Seven fire events are identified at Ballinderry Lough and are spread rather evenly between the present day and 1000BP. Two of these fire events have a magnitude greater than 100 pieces $cm^{-2}peak^{-1}$, and are represented by black crosses in Figure 7.6. The fire eventat 103BP is followed by a decline in biodiversity, represented by a decline in the Shannon Index. The latter fire event shown by a black cross is followed by an increase in Biodiversity in both the Shannon and Simpson's indices. The remaining fire events, represented by the red crosses in Figure 7.6, show a varied response in biodiversity following these fire events with increases and decreases seen in the Shannon and Simpson's indices. The charcoal peak screening carried out for Ballinderry Lough in Chapter 4, however did not produce any 'real fire events'. This may be related to the zero value calculated for the signal to noise index via Kelly's method,

which is seen throughout the record here. Higuera's method however produced an adequate signal to noise index with an average value of 9.1. Looking at the vegetation transitions following these large fire events, Figure 6.1.1 Chapter 6, a varied response is seen both between taxa and between fire events, suggesting that other influencing factors were at play. It is apparent however from the statistical and biodiversity analysis that large fire events are having a negative impact on biodiversity here.

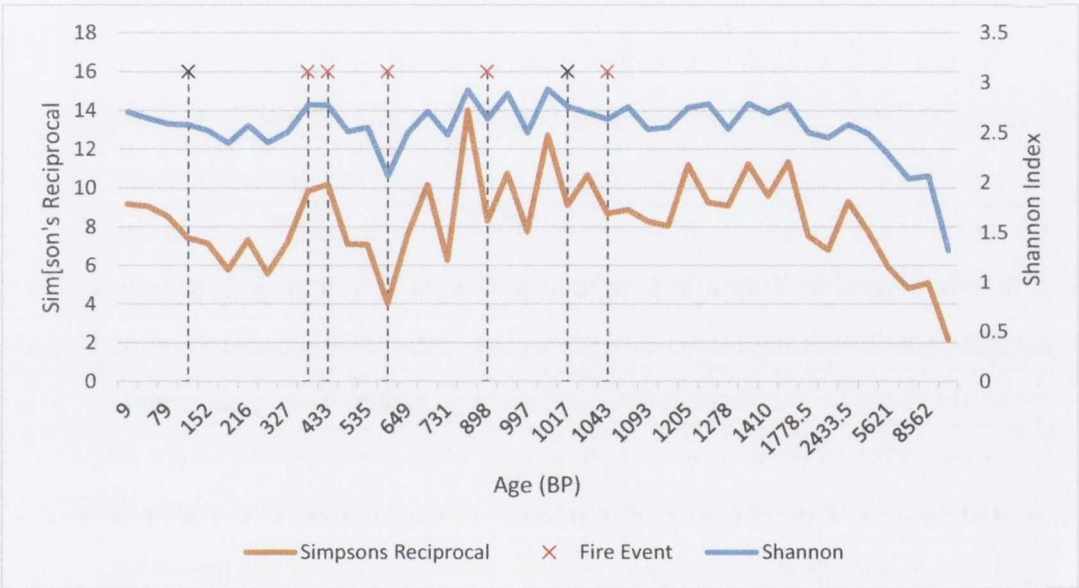


Figure 7.6 Ballinderry Lough fire events plotted with the Shannon and Simpson Indices over time, fire events with a magnitude greater than 100 pieces cm^{-2} $peak^{-1}$ are represented by black crosses, remaining fire events with a lower magnitude are represented by red crosses.

Cornaher Lough

There are eight fire events identified at Cornaher Lough and are clustered between approx. 3700BP and 9800BP. Four of these events have a magnitude greater than 100 pieces $cm^{-2}peak^{-1}$, and are represented by black crosses in Figure 7.7(a). Each of these events are followed by a decline in biodiversity, shown by dips in the Shannon and Simpsons indices. The remaining fire events with a lower magnitude (red crosses) do not always result in a decline in these diversity indices. The effect fire is having on biodiversity appears consistent and striking at this site with fire events of a magnitude larger than 100 pieces $cm^{-2}peak^{-1}$. These fire events can be seen to be associated with declines in tree taxa at this site, such as *Quercus, Ulmus* and *Fraxinus,* and an increase in the dominant species *Corylus,* which can be characterised as a fire dependent taxon. These vegetation transitions can be seen in the pollen diagram for this site Figure 6.1.2 Chapter 6. With reference to the charcoal peak screening carried out in Chapter 4, only one of these higher magnitude events passed the charcoal peak screening procedure here i.e. the event at 3186BP. This may be related to the lower signal to noise index observed at Cornaher Lough via Kelly's method, where 13.6% of the record is greater than the critical value of 3, indicating that the record is appropriate for peak detection. A higher signal to noise index is observed via Higuera's method, with an average signal to noise index of 12.7.

Sheheree Lough

There are two fire events identified at this site at 3870BP and 9750BP, the event at 3870BP has a magnitude greater than 100 pieces $cm^{-2}peak^{-1}$, and is represent by a black cross in Figure 7.7(b). Like the previous events at Cornaher Lough, this event shows a decrease in biodiversity following fire; represented by declines in the Shannon and Simpson

indices here. The biodiversity decreases from a Shannon's index of 2.45 to 2.2 and from a Simpson's index of 7.4 to 5.4. Also similar to the large events at Cornaher Lough, the fire event at 3870BP here is also associated with a subsequent increase in the dominant tree species *Corylus*. Declines in other tree species are also apparent following this event; in *Alnus, Betula* and *Quercus*. These vegetative responses can be seen in the pollen diagram for Sheheree Lough Figure 6.1.4 Chapter 6. Looking at the charcoal peak screening results from Chapter 4, all the fire events at Sheheree Lough passed the charcoal peak screening procedure, and are designated as 'real fire events'. Looking at the signal to noise index calculated in Chapter 4, Kelly's and Higuera's method produced very similar trends at Sheheree Lough. Average signal to noise values of 25.72 and 16.5 respectively, were recorded and 91% of the record at Sheheree Lough was deemed appropriate for peak detection via Kelly's method.

Remaining Sites

The biodiversity and fire event plots for the remaining sites can be seen in Figure 9.3 in the Appendix. These sites contain fire events of a lower magnitude (less than 100 pieces $cm^{-2}peak^{-1}$) and show a varied impact on biodiversity, both between and within study site. The impact of these events is likely to be controlled by a number of factors including, magnitude and severity of fire, climatic conditions, fuel type and load, human activity and specific site characteristics.

a) Cornaher Lough

b) Sheheree Lough

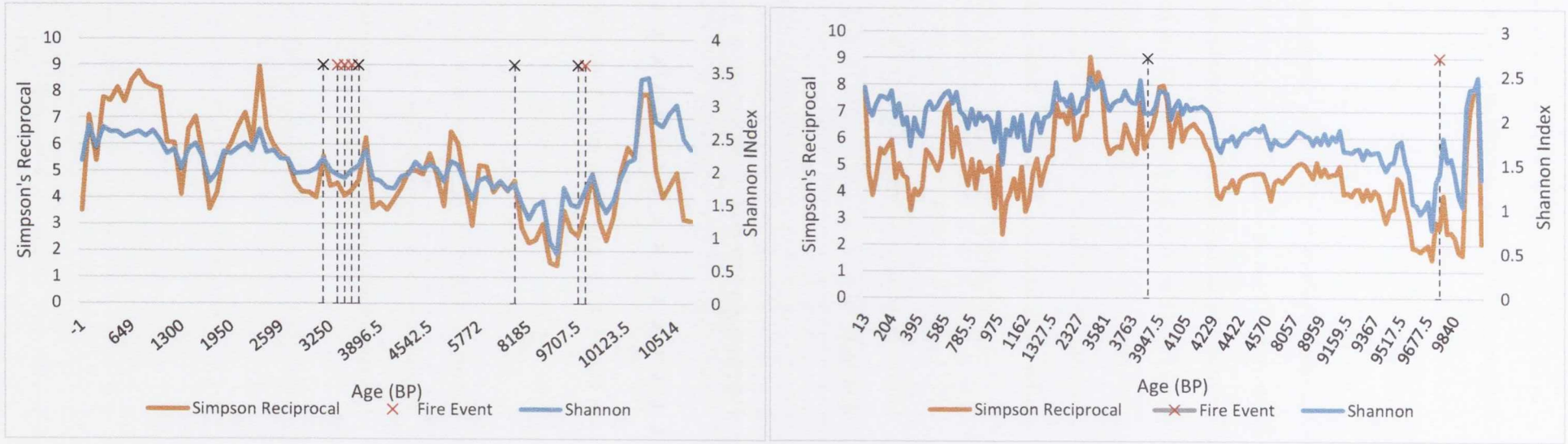


Figure 7.7 Fire events plotted with the Shannon and Simpson Indices over time, fire events with a magnitude greater than 100 pieces cm^{-2} $peak^{-1}$ are represented by black crosses.

7.6 Discussion

With the increasing number of wildfires occurring in Ireland in the past 10 years there are many opportunities for fire to promote or adversely affect biodiversity. Biodiversity extends not only to tree and other plant species but also to animal species (Swingland, 2000) which can be affected by wildfire; however in the case of this chapter and discussion biodiversity refers to vegetative species only. Many studies accept that wildfire can be a significant threat to biodiversity (Alba et al., 2015, Nkwabi et al., 2011, Pastro et al., 2011) however there is a lack of studies which quantify the effects of wildfire on biodiversity, particularly over an extended time scale (Cui et al., 2013, Bush et al., 2008). This study has examined the impact of wildfire on biodiversity during the Holocene at a range of sites throughout Ireland, and is the first study of its kind to statistically analyse if biodiversity is impacted by wildfire.

The biodiversity at each of the study sites was first characterised using a number of diversity indices including Shannon Index and Simpson's Index. A t-test of the overall distributions indicated that with regards to the Shannon Index of biodiversity, Borheen Lough is similar to both Cuckoo Lough and Kelly's Lough. A similar test carried out on the Simpson Index revealed the same results, but in addition a number of other significant comparisons between study sites, where Kelly's Lough is similar to Diheen and Cuckoo Lough, and Borheen Lough is considered similar to Diheen Lough in terms of biodiversity. These results can perhaps be explained by the fact that three of these sites are classed as upland lakes, with an elevation between 476m and 585m, and therefore would be expected to have similar patterns of biodiversity. The fourth site Cuckoo Lough is at a lower elevation of 32m but is located within Killarney National Park, which contains a substantial upland environment, therefore it is possible that this has influenced the similarity in vegetation and biodiversity at Cuckoo Lough when compared to the other upland sites. It is also possible that the underlying geology

surrounding these sites has had an impact on the type and similar patterns of biodiversity; three of the sites at Borheen, Diheen and Cuckoo Lough are all underlain with Old Red Sandstone (Leira et al., 2006) whereas Kelly's Lough is characterised by mainly granite (Farrington, 1966).

Similarities between archaeological time periods were examined with a similar test and there are a wide variety of periods which are considered statistically similar, and this varies significantly between study sites. Some similarities however were noted between Borheen and Kelly's Lough during the Palaeolithic period comparisons. With the most common comparison being made between the Medieval and Modern time periods, which was deemed similar at 6 study sites. This is followed closely by the Iron Age and Medieval, and Iron Age and Modern period comparisons which are significantly similar at four study sites. Each of these three periods are closest to the present day, and their similarities may indicate that there is a large factor affecting the biodiversity in more recent times, a factor such as climate or land-use change. It is clear however with the variation between periods and between sites that there is not only one factor influencing biodiversity here but a network of interrelated elements. Climate is considered to be the main overriding impact on biodiversity, but anthropogenic activity is also an important driver. Seen here and in previous chapters, where there is a significant difference between the data associated with the majority of archaeological periods. These periods are defined based on cultural development, and represent distinct phases in anthropogenic activity.

The evenness at each of the study sites was examined via two separate diversity measures, Pielou's evenness and Simpson's evenness. Similar levels of evenness were observed at the upland sites, Borheen, Diheen and Kelly's Lough which supports the similarity in biodiversity identified previously. The rarity at each of the sites was also calculated and a comparative analysis carried out. Similarities were again observed

between the upland sites at Borheen, Diheen and Kelly's Lough, with Ballinderry and Cornaher Lough also providing similar comparisons; and both these sites are located in Co. Westmeath. The only site that differed was Cuckoo Lough, indicating that largely throughout Ireland the presence and proportion of rare species is similar.

The rank abundance curve and model fit for each of the study sites gives further insight into the nature and similarity of their biodiversity. The two sites from Killarney National Park, Cuckoo and Sheheree Lough, both fit well with the Preemption model, which describes communities with uneven species abundance and a lower diversity characterised by a few dominant species (Magurran, 2013). The upland sites Borheen, Diheen and Kelly's Lough all follow the Zipf-Mandelbrot model, where the presence of a species is dependent on previous physical conditions and species presence, with little role for competition in structuring most assemblages (Gibb et al., 2013). The Zipf-Mandelbrot model also increases in occurrence with stand age and the fit here may therefore represent a more mature population of species surrounding the lakes. Ballinderry and Cornaher Lough fit well with the Log normal and Zipf models respectively. The log normal model usually fits large mature communities and species that arrive split the niche space and occupies a space proportional to their relative abundance (Sugihara, 1980). Zipf models are closely related to the Zipf-Mandelbrot model, where pioneer species require few prior conditions and late successional species require more conditions and are thus rarer. These models give an indication of the type of communities that they describe and which are ultimately built on the specific site conditions and numerous climatic and environmental factors affecting each site (He and Legendre, 2002)

The analysis of rarefied richness has identified a similar pattern between archaeological periods and study sites. The Medieval and Modern periods show the highest species richness across each of the study sites, with the Palaeolithic and Mesolithic periods generally showing the

lowest richness. The only site that partially violates this pattern is Borheen Lough, where the Palaeolithic period has one of the highest levels of richness. Most sites follow what would be expected following the last glacial maximum and the re-colonisation of species. In general there would be a lower species richness during the Palaeolithic at the beginning of the Holocene, which would generally increase as climate conditions improved (Pereira et al., 2012). The last glacial maximum is found to have had a significant impact on the richness and distribution of species, with species spreading out from a number of glacial refugia, where species richness is higher (Normand et al., 2011). A number of studies support the hypothesis that species distribution, richness and diversity have been in equilibrium with climate throughout most of the Holocene (Turner et al., 1996, Webb III, 1986, Huntley and Webb, 1989, Tinner and Lotter, 2006). Which would suggest that the patterns in richness seen here can partially be explained by climatic factors and land-use changes. A similar study of richness throughout the Holocene in Northern Europe by Giesecke et al. (2012) showed that an increase in richness in the last 1000 years was due to human land-use. The study however also acknowledges the difficulty in separating the factors potentially influencing biodiversity.

Examining the relationship between rarefied richness at each of the study sites, a different pattern of similarity emerges than was previously identified by the other diversity indices. The similarities occurred between Kelly's and Ballinderry Lough, and between Cornaher and Borheen Lough. The model fits may shed some light on these similarities as Borheen Lough is associated with the Zipf-Mandelbrot model and Cornaher Lough fit well with the simpler Zipf model the two describe communities that are based on similar principles of colonisation and succession. Kelly's Lough and Ballinderry Lough follow different models, the Zipf-Mandelbrot and Log normal model respectively. This suggests that similar communities described by these models will produce a

similar level of species richness; determined by surrounding environmental and anthropogenic factors.

A comparison between the rarefied richness across archaeological periods at each site yielded five comparisons that were statistically similar. The Palaeolithic period was classed as similar to both the Mesolithic and Neolithic periods, while the Modern period is similar to the Medieval and Iron Age period. The final statistically similar comparison is between the Medieval and Bronze Age period. Considering a unifying causal factor it is possible that the climate was similar in these periods, causing the pattern in richness to be similar; or perhaps a disturbance factor such as fire was higher during these periods having a significant effect on the richness. Looking at temperature reconstructions from the Swiss Alps throughout the Holocene based on chironomid data they demonstrate an exponential increase in temperature during the Palaeolithic and Mesolithic from 12,000BP to 4000BP, which predates any major human impact. This may account for the similarity in richness during the Palaeolithic and Mesolthic periods. By the later Modern, Medieval and Iron Age time periods from 3,500BP to the present day the temperature is ~1°C lower (Heiri et al., 2003).The Bronze Age is generally regarded as a period of decreased average temperature (Lamb and Woodroffe, 1970, Houghton, 1996), before moving to the slightly warmer periods during the Medieval. The Bronze Age is preceded by the so-called 4.2 ka event which has been identified as a cool/wet phase from bog surface wetness records at a number of sites in Northern England (Chiverrell, 2001, Charman et al., 2006, Barber and Langdon, 2007), Scotland (Langdon and Barber, 2005) and Ireland (Swindles et al., 2013). Temperature reconstructions can be used to give an insight into the similarities between archaeological time periods but it should be noted that this is a general trend and should be treated with caution as temperature varies spatially throughout Europe (Davis et al., 2003), and other factors such as rainfall, humans or extreme events may

be impacting the biodiversity of such time periods (Heller and Zavaleta, 2009).

The interaction between biodiversity and fire was examined using rarefied richness before and after each fire event in a 200 year time window using a paired t-test. The results were not statistically significant indicating that there is no significant difference in biodiversity before and after a fire event at any of the study sites. The magnitude of a fire necessary to impact biodiversity was then examined and fires with a larger magnitude produced smaller p-values, indicating that fire is having an increasing impact on biodiversity as magnitude of fire increases. As fires become more frequent and intense with increased climate change, they are likely to have an increasingly negative impact on biodiversity. Pastro et al. (2011) and Pausas and Keeley (2009) back up the fact that fire has an impact on biodiversity, and Kelly et al. (2015) has conducted a study to determine the optimal fire characteristics for biodiversity conservation. It is clear from this study and other similar studies (Giljohann et al., 2014, Taylor et al., 2013, Driscoll et al., 2010) that fire management is important in the conservation of biodiversity and fire suppression is not an adequate response; in fact paradoxically it can increase the impact of wildfires (Marlon et al., 2012). Pyne (2001) also aptly states that "Biodiversity can be lost as surely through fire exclusion as through fire excess." Changes in biodiversity can also promote a response in fire frequency, where there is a significant ecosystem change. This does not appear to be the case in this study, however documented an increase in fire frequency following grass invasion and removal of woodland.

How biodiversity changes over time and in response to specific fire events was examined through a simple plot of the Shannon and Simpson diversity indexes and fire events over time. Each site displays significant oscillations in biodiversity, and a number of common patterns can be identified. Biodiversity was generally lower prior to 10,000BP, before

increasing steadily across all sites towards the present day. There is a dip in biodiversity around approx. 4000BP which may be in response to the 4.2ka event which was a period of abrupt climate change (Roland et al., 2014). A number of declines in biodiversity can also be seen and coincide with two major phases of human activity at approx. 1100BP and 5900BP as identified by Berglund (2003). A dip in biodiversity at approx. 200BP across all study sites emphases the modern impact factors such as climate and increased extreme events are having on biodiversity. At three sites Ballinderry, Cornaher and Sheheree Lough fire events larger than 100 pieces cm^{-2} $peak^{-1}$ showed a unified decrease in biodiversity; represented by a decline in the Shannon and Simpson indices. This suggests that fires of this magnitude are negatively impacting biodiversity. These events were also identified to have a similar impact on the vegetation, with declines observed in tree species such as *Quercus, Alnus, Ulmus, Betula* and *Fraxinus,* and an observed increase in the dominant species *Corylus.* These large fire events are concentrated dominantly in the Bronze Age with three events between 3100BP and 3900BP. This was period of reduced temperature across Europe (Davis et al., 2003) and a period of heightened human activity in Ireland (Molloy and O'Connell, 1991, O'Connell et al., 1988) which was followed by climate deterioration and the collapse of the Late Bronze Age population (Armit et al., 2014). Therefore these earlier higher magnitude fires may be the result of anthropogenic activity within the landscape. The later fire events at 7155BP and 9707BP may be associated with changes in climate such as increased temperature or dryness, which have promoted a significant decrease in biodiversity. The remaining sites with lower magnitude fires, showed a varied response in biodiversity following fire events. A similar response can be seen in a study of grassland fire in Hungary (Deák et al., 2014) which showed that burning can have both a positive and negative effect on biodiversity.

This study has examined changes in biodiversity at seven sites throughout the Holocene, exploring three interconnected factors; fire, climate and human activity which can influence biodiversity. Larger magnitude fires typically greater than 100 pieces $cm^{-2}peak^{-1}$ were observed to have a negative impact on biodiversity, suggesting that the direct impact of a fire depends on its magnitude and intensity. Species richness, diversity indices and specific vegetation show a marked change following fire, and can be observed in other boreal and tropical forests e.g. Moretti et al. (2004). The driver of biodiversity change in Ireland appears to be an interaction between climate, humans and fire activity. This is supported by a study of long term changes in biodiversity across central and southern Europe, which highlighted that climate and human impacts also play a significant role in biodiversity change, and the impact of fire on biodiversity is varied depending on these other influencing factors (Colombaroli and Tinner, 2013). As fire frequency and intensity is predicted to increase in the future (Marlon, 2013) the impact of fire on biodiversity within Ireland is likely to increase, especially as larger fires have been proven here to negatively impact biodiversity.

7.7 Conclusion

This chapter presents a detailed investigation into biodiversity change at seven study sites throughout Ireland, and examines how this biodiversity is impacted by specific fire events. From the numerous statistical analyses presented a number of conclusions can be drawn;

1. Fire events were compared across all study sites, however biodiversity was not identified to significantly change (p-value 0.449) following a fire event.
2. Fires with a larger magnitude (typically >100 pieces cm^{-2} $peak^{-1}$) have been shown to have an increasingly negative impact on biodiversity.
3. Biodiversity was lower during the Palaeolithic and Mesolithic across each of the study sites following the impact of the last glacial maximum.
4. The study sites in Ireland follow a similar general trend in biodiversity throughout the Holocene with specific fluctuations at each site dictated by varied conditions.
5. It is clear that there is not a sole driver of biodiversity change, but there are significant factors, mainly climate, humans and fire, which are interrelated to shape changes in biodiversity.

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Chapter 8

Discussion

8.1 Overview

Fire is an enigmatic, dominant and altering force of nature which has helped to shape life on earth for the past 350 million years (Scott and Glasspool, 2006). It is the dominant disturbance in most terrestrial ecosystems (Bowman et al., 2009), and there are few places on earth that escape its reach (Krawchuk et al., 2009). In recent years climate change has promoted an increase in the frequency, scale and intensity of wildfire (Marlon et al., 2013), not only in tropical regions but also temperate regions (Westerling et al., 2006a). Ireland is no exception to this increase, and a combination of human and climate influences are thought to be the main drivers of fire. This thesis addresses a number of questions arising about the nature, scale, impact and pattern of fire within the Irish landscape. Utilising lacustrine charcoal and pollen records from the early Holocene (approx. 12,000BP) to the present day, to reconstruct the past landscape and fire regimes at seven study sites spread throughout Ireland. A range of ecosystems are examined in an upland (Borheen, Diheen and Kelly's Lough), lowland (Cuckoo and Sheheree Lough) and midland (Cornaher and Ballinderry Lough) environment to address four main research questions;

1. What was the nature and scale of fire in the Irish landscape in the past?
2. Are there common trends in fire that can be identified on a national and international scale?
3. How did this fire impact the surrounding landscape and vegetation?
4. Does fire have an impact on biodiversity and on what level?

8.2 Fire in the Irish Landscape

Fire events, their frequency and magnitude were reconstructed from the seven study sites, with a differing number of fire events identified at each site; the lowest number of fire events was identified at the lowland sites of Killarney National Park at Cuckoo and Sheheree Lough, with 4 and 3 events respectively. A larger number of fire events were identified at the upland sites with 10 fire events at Diheen Lough and 5 at Borheen Lough in the Galty Mountains, and 5 at Kelly's Lough in the Wicklow Mountains, which may suggest a sensitivity to fire in the uplands. The magnitude of fires varied greatly between the study sites and is likely to be function of the fuel type, weather conditions, and ignition source. Fires with a magnitude larger than 100 pieces cm^{-2} $peak^{-1}$ were identified at Ballinderry, Cornaher and Sheheree Lough, these sites are located at lower altitudes, in a similar vegetative environment. Fires in the uplands tended to be of lower magnitude but more frequent in occurrence, with higher fire frequency values recorded from the Galty Mountains. The fire return intervals also differed between sites, reflecting the varied distribution of fire events and differing temporal scales. Fire return intervals are useful in helping to predict when a future fire is likely to occur. Longer fire return intervals were calculated from the sites in Killarney National Park, Cornaher Lough in the Irish Midlands and Kelly's Lough in the Wicklow Mountains. The shortest mean fire return interval occurred at Diheen Lough with 65 $yr.fire^{-1}$. The methods used to carry out these reconstructions were assessed and deemed to be valid, providing an accurate process for fire event identification. New methods were tested such as an updated signal to noise index (Kelly et al., 2011), ensemble member strategy (Blarquez et al., 2013) and charcoal peak screening (Finsinger et al., 2014). It is clear from these reconstructions that a different fire regime exists specific to each of the study sites, which is likely to be influenced by a variety of catchment conditions.

8.3 Fire and Vegetation

The relationship between fire and vegetation was examined at each of the study sites and a number of general trends associated with specific taxa have been identified. Specific taxa can be designated as fire adapted (*Quercus, Pinus* and Poaceae), fire dependent (*Corylus, Alnus, Pinus* and *Salix*), fire resistant (*Betula, Quercus, Pinus,* Poaceae and *Calluna*) and fire sensitive (*Ulmus*). Fire adapted species have the ability to survive fire and have potentially evolved with specific traits such as thicker bark or serotinous cones to help limit the impacts of fire. Fire dependent species rely on fire to promote their growth and expansion and readily regenerate post-fire. Finally fire resistant species are more likely to survive fire whereas fire sensitive species are likely to be negatively impacted by fire. The response of these specific taxa was largely unified across each of the study sites, depending on the magnitude of the identified event. This will potentially help in future scenarios to predict the response of an ecosystem to fire based on its vegetation composition. Vegetation reconstructions were identified as similar based on geographical location, and largely represent common oscillations which have previously been identified as characteristic to Ireland e.g. evidence of the *Pinus* and *Ulmus* decline. The vegetation composition was also deemed distinct between archaeological time periods helping to characterise vegetation change. The early Holocene can be characterised by rapid climate change and plant immigration, possibly due to increased temperature following the last glacial maximum, and is demonstrated at numerous sites here with widely spaced samples in the ordination analysis pre 9000BP. The present day is deemed similar to the early Holocene between 10,000 and 13,000BP, represented in the ordination analysis, suggesting that the present day is experiencing a similar vegetation composition to the early Holocene. Fire events are also seen to be represented close to the present day at a

number of sites within the ordination plots, indicating that fire events are possibly increasing towards the present or are occurring under similar conditions. The events tend to be clustered within the ordination space at the majority of sites suggesting that fire events were occurring within similar time periods or under similar vegetation and climate conditions. These relationships are backed up in the statistical analysis with significant p-values from the ANOVA analysis. The highest periods of vegetation change and instability are seen to be associated with the identified fire events, reflected in the rate of change analysis, suggesting that fire was a major disturbance in the landscape.

8.4 Fire and Biodiversity

Biodiversity was reconstructed throughout the Holocene at each of the study sites from palynological records, and was identified to be lower during the Palaeolithic and Mesolithic periods across all of the sites, following the impact of the last glacial maximum. There is a dip in biodiversity around approx. 4,000BP which may be in response to the 4.2ka event which was a period of abrupt climate change (Roland et al., 2014). A dip in biodiversity at approx. 200BP across all study sites emphasises the modern impact factors such as climate and increased extreme events are having on biodiversity. The biodiversity of the different archaeological periods was compared via a t-test and the periods closest to the present day were identified as statistically similar across the majority of sites. This may indicate that there is a stronger influencing factor affecting biodiversity in recent years. Models were fitted to the data from each of the sites to try and theoretically describe the data. Geographical area appeared to be a factor in determining model fit; the upland sites all fit well with the Zipf-Mandelbrot model, while the sites in Killarney National Park fit well with the Pre-emption model, and the sites of the Irish Midlands fit well with the Log normal

and Zipf models. This indicates that similar communities are found in adjacent geographical areas, controlled by factors related to the study sites, climate and the surrounding environmental conditions. Oscillations in biodiversity were examined in reference to the identified fire events and biodiversity was not seen to significantly change (p-value 0.45) following a fire event. Not all events show a consistent impact on biodiversity, and the impact varies both within and between sites. To try and quantify the impact of fire on biodiversity fires were examined at a range of magnitudes, and as fire magnitude increases the associated p-values decrease. This suggests that larger fires are having an increasingly significant impact on biodiversity, and as fire frequency, intensity and magnitude increases in the future in conjunction with climate change, there is likely to be an increasingly negative impact on biodiversity. The study sites in Ireland follow a similar general trend in biodiversity throughout the Holocene with specific fluctuations at each site dictated by site conditions. Three sites Borheen, Diheen and Cuckoo Lough are identified to have statistically similar patterns of biodiversity, which is perhaps in part related to the similar geology at each of the sites; they are all underlain with Old Red Sandstone. It is evident from this analysis that fire or climate are not the sole drivers of changes in biodiversity but are significant contributors, and other factors such as humans, extreme events, site characteristics and additional climatic conditions also play a role in shaping changes in biodiversity. Studies such as this are important for future scenarios where fire frequency and intensity is predicted to increase (Marlon, 2013); the impact of fire on biodiversity within Ireland is also likely to increase, especially as larger fires have been proven here to negatively impact biodiversity.

8.5 Trends in Fire

Trends in wildfire were investigated across the seven study sites within Ireland to determine possible drivers of these trends at a variety of geographical scales. A number of fire events were identified as synchronous on a regional scale, with respect to upland and lowland ecosystems. The upland sites of Borheen, Diheen and Kelly's Lough, with a similar altitude, vegetation and biodiversity appear to be displaying a number of similar fire events. This can be compared to Ballinderry Lough where the events appear to occur slightly later than at the upland sites suggesting a delayed response to drivers of fire in the lowlands. Two synchronous events are identified at Cornaher and Sheheree Lough and occur at 9,751BP and 9,752BP respectively. These two sites are in the lowlands at a similar altitude and have a similar vegetation composition. From 2,000BP to the start of the Holocene it is more difficult to identify any synchronous fire events between the study sites with a gap of less than 100 years. This appears to show an increased synchroniety of events towards the present day and it can be hypothesised that an overall influencing factor such as climate or human activity is having an increasingly regional effect. A k-s test between study sites and archaeological periods also highlights the idea of increased synchroniety in the later Holocene, with all significant comparisons between 4,400BP and the present day. Fire return intervals were examined across the sites and their distribution is related to the identified fire events. Adjacent sites produced significant comparisons suggesting that location and study site characteristics are important in influencing the nature of fire regimes. At smaller spatial scales such as this there are also variations in fire occurrence which can be explained by factors such as location of ignition, fuel load, flammability, topography and specific weather conditions. Looking at the magnitude of fire events, regional trends appear to be apparent with significant comparisons between the upland sites of Borheen, Diheen and Kelly's Lough, and adjacent sites in the

lowlands, Ballinderry and Cornaher Lough, and Cuckoo and Sheheree Lough. This indicates that fires occurring in the same region are likely to have a similar magnitude, influenced by factors such as vegetation type, moisture content, fuel load and meteorological conditions. A composite record for Ireland was produced which was compared to composite trends in fire from the UK, Europe, North America and the World. The composite record of fire from Ireland follows similar trends in fire from the UK, Europe, North America and the World. The general trend across all of the sites is that fire was low in the early Holocene from approx. 15,000BP, and increases steadily towards the present day with numerous oscillations which are assumed to be attributed to variations in influencing factors such as human activity or climate. There is a significant decrease in charcoal activity at 13,250BP in the Irish and UK records, after which there is a sharp rise in fire activity. A marked peak in charcoal can then be seen at 11,250BP in the UK, Irish and European records. The records from Europe, North America and Worldwide display a smoother trend but all follow a similar general trend in charcoal. Noticeable commonalities can be seen where fire activity peaks at 9,750BP, 11,250BP and 12,750BP in all regions. A marked decrease in fire activity is apparent in all areas except Ireland at 14,250BP, with the Irish record decreasing slightly later at 14,750BP. Another lull in activity occurs around 4,750BP at all sites before generally increasing towards the present day. It is clear from this analysis that fire can be related to a number of factors at regional and global scales, including temperature, precipitation and oscillations in atmospheric CO_2. Increases in CO_2 promote an increase in vegetation production which could increase fuel loads, leading to more frequent and intense wildfire. A k-s test was used to compare the composite records and the majority of comparisons produced statistically similar results, indicating that the Irish record follows similar trends to those of the UK, Europe and North America. It was only the worldwide record which produced a differing result. From this analysis it is clear that the Irish sites largely display independent fire

regimes at a local scale, but the composite record highlights how the general trend for Ireland is in agreement with trends in wildfire from across the globe with factors such as climate change and increased human activity having a mass impact in the occurrence and pattern of wildfire at a variety of scales.

8.6 Fire and Humans

It has been widely accepted that humans have been using fire in a variety of ways throughout the Holocene, having significant and altering impacts on the surrounding landscape. At the beginning of the Holocene all continents except Antarctica, were settled by humans (Marlon, 2013) providing a significant record to utilise in disentangling climate and human influences on changing fire regimes in various regions. Human activity is an important factor that could potentially affect global fire regimes. Characterising fires as human or natural from the palaeo-record is an ongoing challenge, due to the complex nature of human, climate and fire interactions. Records should be interpreted on a multi-proxy basis and we must rely on the synchronicity of events with indicators of human activity (Marlon, 2013) to provide the best available reconstructions. Global wildfire is dictated by factors such as climate, vegetation, humans and land use, which have been in fluctuation with increases in atmospheric CO_2 since the onset of climate change (Prentice et al., 2011). Studies assessing these interactions at global scales over millennia (Marlon et al., 2008) have attributed climate to be the dominant driver of fire activity (Daniau et al., 2010, Mooney, 2011, Power et al., 2013). This study has highlighted a number of trends that exist between fire and human activity within Ireland. Fire events exist at Cornaher, Cuckoo and Sheheree Lough which predate human occupation and can therefore be attributed to natural causes. However as you move closer to the present day the Medieval period stands out as a significant

period having increased fire activity, and was a period of increased temperature and human activity. Fire events with a magnitude larger than 100 pieces $cm^{-2}peak^{-1}$ are concentrated dominantly in the Bronze Age with three events between 3100BP and 3900BP. This was a period of reduced temperature across Europe (Davis et al., 2003) and a period of heightened human activity in Ireland (Molloy and O'Connell, 1991, O'Connell et al., 1988) which was followed by climate deterioration and the collapse of the Late Bronze Age population (Armit et al., 2014). The analysis appears to show that the synchroniety of events is increasing towards the present day and it can be hypothesised that an overall influencing factor such as human activity or possibly climate is having an increasingly regional effect towards the present day. A number of declines in biodiversity can also be seen to coincide with two major phases of human activity at approx. 1100BP and 5900BP as identified by Berglund (2003). With the main driver of biodiversity change in Ireland being attributed to an interaction between humans, climate and fire activity. During the past two centuries, anthropogenic activities have dominated the global biomass burning signal (Marlon et al., 2012), and factors such as population growth, fire suppression, land use change, agriculture, overgrazing, urbanisation and invasive plants, have caused changes in fire regimes (Bowman et al., 2011). The composite trends identified in this analysis would also suggest that global factors such as increased human activity and climate change are having a mass impact in the occurrence and pattern of wildfire on an international scale. Similarly Ruddiman (2003) has argued that human use of fire for land clearance explains the increase in CO_2 and CH_4, having a significant impact on climate during the early/mid-Holocene. The subsequent rise in biomass burning being linked to increasing human influences such as population growth and land use change (Marlon et al., 2008). The clear separation of archaeological periods in the statistical analysis at each of the study sites here, signifies that human impact on the landscape is a significant driver of biodiversity after climate. It is clear from this study

and other analyses that changes in land use or human activity are not sufficient alone to explain the record of biomass burning at a regional or continental scale during the Holocene, although they do play a significant role at the local scale.

8.7 Fire and Climate

Climate is one of the main factors influencing wildfire globally; it exists in conjunction with other forcing factors such as vegetation, humans and land use. Patterns of fire have been linked to fluctuations in atmospheric CO_2, which have increased with the onset of climate change (Prentice et al., 2011). With this increase there has been a wide concern for the implications that this will have on wildfire (Westerling et al., 2006b), with many hypothesising that wildfire will increase in the future (Girardin and Mudelsee, 2008), creating more frequent and intense impacts on the environment and people (McKenzie et al., 2004, Gonzalez et al., 2010). Future climate predictions for Ireland indicate that temperatures are to continue to increase, and summers are to become drier with up to a 20% reduction in precipitation (Gleeson et al., 2013). This will increase the vulnerability of the Irish landscape to wildfire, therefore studies such as this are essential to identify and quantify the drivers and patterns of wildfire in Ireland in the past, which will help to predict and manage the future impacts of wildfire.

Climate has been identified as a significant driver of fire at a variety of scales (Marlon et al., 2013, Liu et al., 2010, Bowman et al., 2009), with global wildfire increasing and decreasing throughout the Holocene (Marlon, 2013) reflecting patterns of climate change (Aldersley et al., 2011). The early Holocene was characterised by rapid climate change and plant immigration, possibly due to increased temperature following the last ice age and is demonstrated at numerous sites in this study. More recently Calvo et al. (2014) has stated that changes in CO_2 concentration

are a major factor in changing global fire patterns, especially between glacial and interglacial periods. Mauri et al. (2015) demonstrated a decrease in precipitation in Europe during the Early Holocene from 12ka to 11ka, which may help to explain the widespread peaks in fire activity identified at this time. Marlon et al., (2013) also found that there is an increase in biomass burning at approx. 10,000BP coinciding with a rapid rise in July temperatures (Viau and Gajewski, 2009).

At four of the study sites here, Ballinderry, Borheen, Diheen and Kelly's Lough the majority of fire events are occurring close to the present day, suggesting that fire has been increasing in recent years at these sites and occurring in periods where climate and vegetation conditions were similar. The Medieval period was identified as the most active in terms of fire events, with 17 in total, spread across Ballinderry, Borheen and Diheen Lough. This period coincides with the 'Medieval Warm Period' which is characterised by a period of increased temperature (Goosse et al., 2006). Cui et al. (2014) also reported an increase in fire activity from 2.5ka to the present day due to an increase in temperature in Europe. The Late Holocene and Late Palaeolithic have therefore been characterised by increased levels of fire due to increased temperature and increased biomass. This is backed up by evidence suggesting that at a number of sites the present day was deemed similar to the early Holocene between 10,000 and 13,000BP, suggesting that the present day is experiencing a similar vegetation composition and similar climatic conditions. Generally results show that identified fire events are associated with periods of instability and change, and generally occur within similar time periods or under similar vegetation and climate conditions. Fire events tended to be clustered together within the ordination analysis and are also seen to be represented close to the present day at a number of sites; again suggesting that fire events were occurring within similar time periods or under similar vegetation and

climate conditions, and possibly indicating that they are increasing towards the present day.

Climate change has been the catalyst to focus discussions on biodiversity conservation and management, with the increase in extreme events such as fires contributing to habitat degradation, species loss and an overall decrease in biodiversity, putting ecosystems in an increasingly vulnerable position. Currently there is abundant evidence that climate change impacts biodiversity and it is likely to become one of the most significant drivers of biodiversity loss by the end of the century (McMahon et al., 2011, Beaumont et al., 2011, Dillon et al., 2010). Climate change is already forcing biodiversity to adapt either through shifting habitat, changing life cycles, or the development of new physical traits (Botkin et al., 2007). Due to these changes in climate species may no longer be adapted to the set of environmental conditions in a given region and could therefore fall outside of their climatic niche (Bellard et al., 2012). Species can respond to climate change along three axes; space e.g. range, time e.g. phenology, and self e.g. physiology. Species can shift spatially tracking suitable climatic conditions. They can also shift temporally in the timing of life cycle events such as flowering and fruiting (Charmantier et al., 2008). Lastly species can cope with climate change by adapting themselves to the new conditions. Physical alterations can allow tolerance to warmer or drier conditions, or behaviour modifications to diet or activity (Johansen and Jones, 2011). As the scale, intensity and level of destruction caused by wildfire is increasing in conjunction with climate change; species can protect themselves by adapting traits such as thicker bark, non-flammable foliage, thick clusters of needles to cover buds, or serotinous cones (Pausas and Keeley, 2009). A number of studies support the hypothesis that species distribution, richness and diversity have been in equilibrium with climate throughout most of the Holocene (Turner et al., 1996, Webb III, 1986, Huntley and Webb, 1989, Tinner and Lotter, 2006).Which would suggest that the patterns in richness seen

here can partially be explained by climatic factors. Results from this study also suggest that patterns and oscillations in biodiversity throughout the Holocene closely follow patterns in climate. A dip in biodiversity at approx. 200BP across all study sites emphases the modern impact factors such as climate change, modern landuse and increased extreme events are having on biodiversity.

It is clear from this analysis and other studies that climate is one of the main drivers of fire at regional, national and global scales, fostering climate change and complex interactions between humans, vegetation and fire. The effects of which are predicted to increase in the future.

8.8 Future Recommendations

This study has provided an overview of fire throughout the Holocene at a range of geographical locations within the Irish landscape, and represents the first study of its kind in Ireland. It is the hope that this work can be built on in future scenarios when fire frequency and severity is predicted to increase. Valuable knowledge has been gained in identifying the nature and pattern of fire, how it interacts with the Irish vegetation, how it impacts biodiversity and how it varies between ecosystems. In order to plan for future scenarios it is important to understand the main drivers and effects of fire and this thesis has endeavoured to create a background for future study of fire in the Irish landscape. Studies such as this are necessary to inform management and policy guidelines to help reduce the negative impacts of fire in the future, and it is the hope that significant patterns identified here will help to guide future work.

Some practical advice for fire management in Ireland includes; ensuring that excess fuels do not accumulate, especially in dry conditions. Excess fuels can be removed via prescribed burning but national guidelines

should be strictly followed. Weather conditions should be observed and it's important to be vigilant during extended dry periods. Fire breaks can be adopted in vulnerable areas to hinder the spread of wildfire. Finally and possibly the most important, the public should be educated on the impacts of wildfire to help reduce anthropogenic ignitions.

An aspect of analysis which is lacking here is predicting future patterns of wildfire. This embodies a substantial amount of work which was not achievable in the timescale here, but would provide valuable insights for the management of future fire and landscapes.

It would also be advantageous to explore further the relationship between wildfire and anthropogenic fire and the surrounding landscape, to try and discover if there is a way to distinguish between them in the palaeo-record, perhaps based on intensity, magnitude, area burned or type of material burned. Another potential area of research would be to try and calibrate the fire records, and compare them to modern fires or documentary evidence, to determine what a specific magnitude or intensity of fire looks like in the landscape.

Also within this study an elemental analysis was attempted at a number of sites using the Itrax Core Scanner (Croudace et al., 2006) to determine element profiles and magnetic susceptibility. This provides an additional proxy for environmental change and disturbance, however due to the high water content and degradation of a number of the cores a complete analysis could not be carried out; but would be useful if feasible in future studies.

A number of new statistical methods were tested here to validate the fire history reconstruction. An ensemble member strategy (Blarquez et al., 2013) an improved signal to noise index (Kelly et al., 2011) and charcoal peak screening method were adopted (Finsinger et al., 2014). These methods supplement and validate the fire history reconstructions and are discussed in detail in Chapter 4. They are recommended for use in

future charcoal analyses in conjunction with the CharAnalysis programme which provided accurate fire event identification here.

8.9 Conclusion

Fire is an important ecological disturbance whose impact has been felt across the globe. It responds to changes in climate, vegetation, human activity and land use; and its frequency and severity are likely to increase with projected future climate scenarios. Fire is reflected in the Irish landscape in varying vegetation responses and changes in biodiversity. This study has reconstructed the past fire regimes at seven sites spread throughout the Irish landscape, in upland, lowland and midland environments. The largest magnitude fires are identified to occur in the Bronze Age and at lowland site, suggesting a link to anthropogenic activity and humans playing a key role in fire intensity. Past landscape reconstructions reflect vegetation transitions throughout the Holocene and assess how fire impacts specific taxa. Charcoal taxa correlations are uniform across the majority of sites, however the sites within Killarney National Park display a varied response to fire activity. Biodiversity change is also addressed on an extended time scale, and the impact of fire is examined at a range of magnitudes. This research has revealed a hierarchy of drivers of biodiversity which interact at a range of spatial scales i.e. climate, humans and then fire. It has identified fires of a larger magnitude to have an increasingly significant impact on biodiversity. Trends in wildfire are identified at a regional, national and international scale, comparing fire events between sites and utilising composite charcoal records. With trends identified at the Irish sites coinciding with oscillations seen in the UK, Europe, North America and the World composite records. Numerous statistical analyses and software are also used to quantify any relationships and patterns which exist between fire and the various parameters examined. This study provides a base line

level of data for fire history reconstruction in Ireland which will hopefully be built on in the future. It is clear from this research that fire has a significant local impact but due to the resolution of proxy records (e.g. pollen and charcoal) from lake sites, only large impacts are detected. This can be seen in the biodiversity analysis where fires with a higher magnitude show a larger impact. Whereas smaller peaks which are widespread throughout the record have a minimal impact on biodiversity. This research has revealed that fire has not been a major driver in the Irish landscape, however future climate predictions suggest that the frequency and intensity of fire will increase; and this research has demonstrated that fire has the potential to have a significant impact on the landscape and negatively impact biodiversity. Although large effects were rarely seen in the palaeo-record, the potential impact with future climate change, increased temperatures and reduced precipitation, is expected to be large.

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Appendix

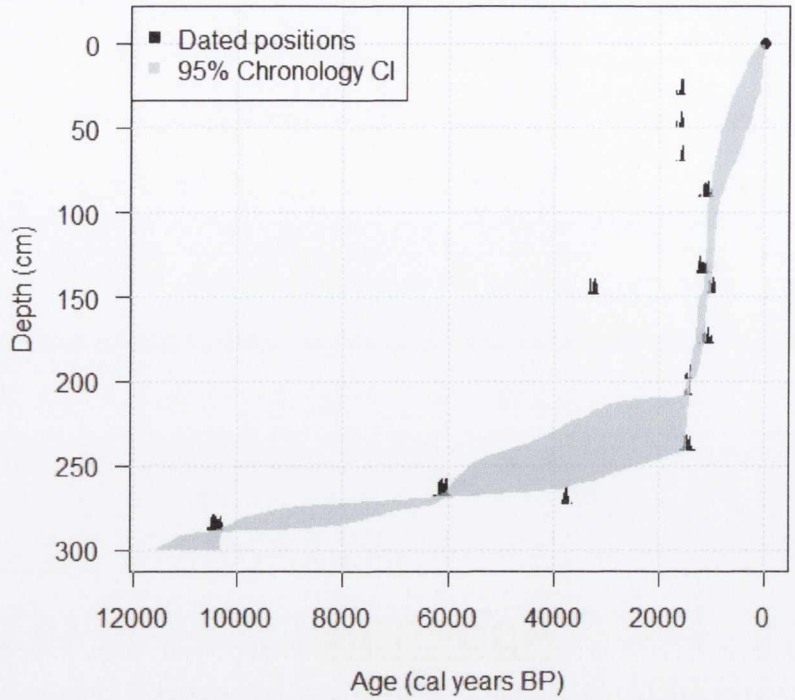


Figure 9.1.1 Chronology for Ballinderry Lough

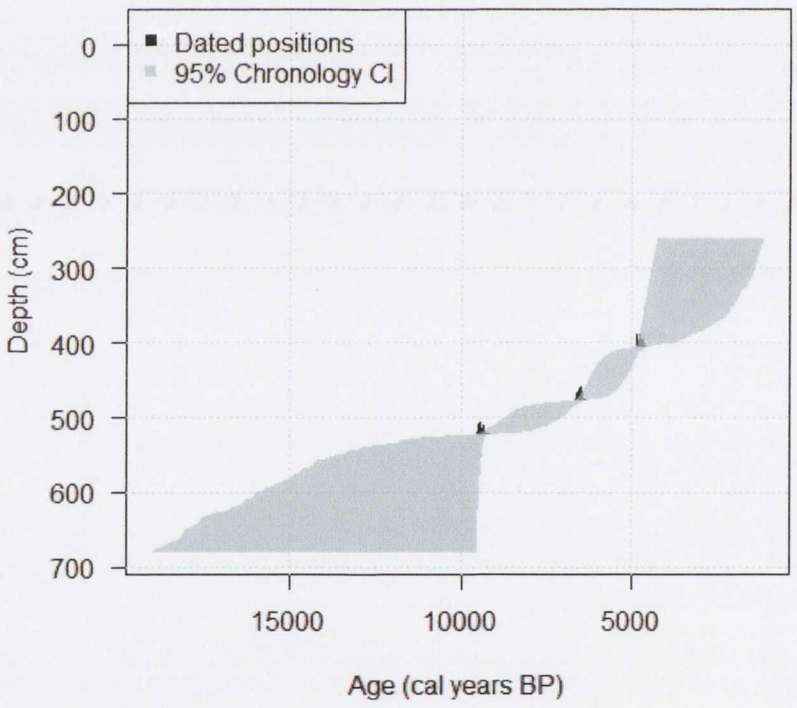


Figure 9.1.2 Chronology for Cornaher Lough

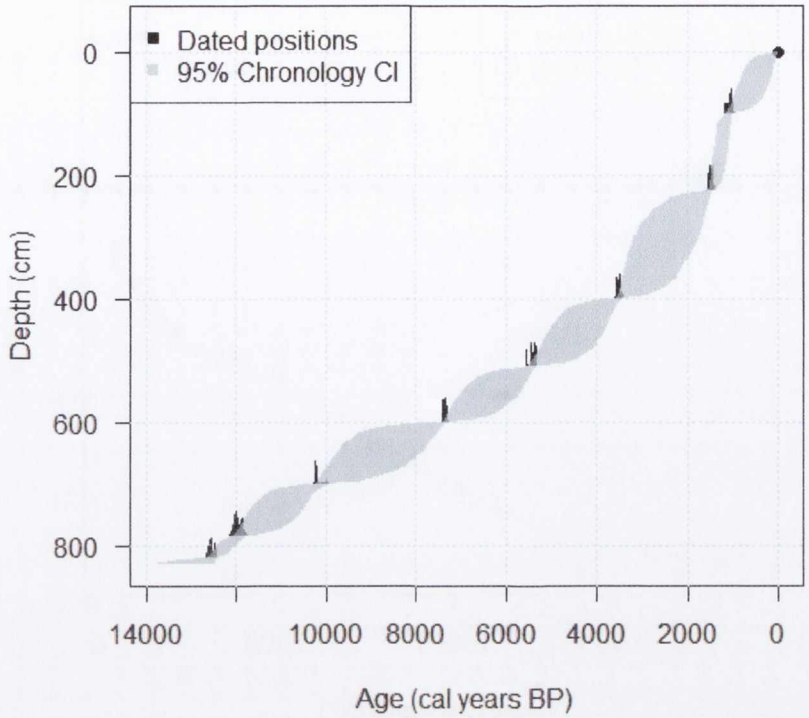


Figure 9.1.3 Chronology for Borheen Lough

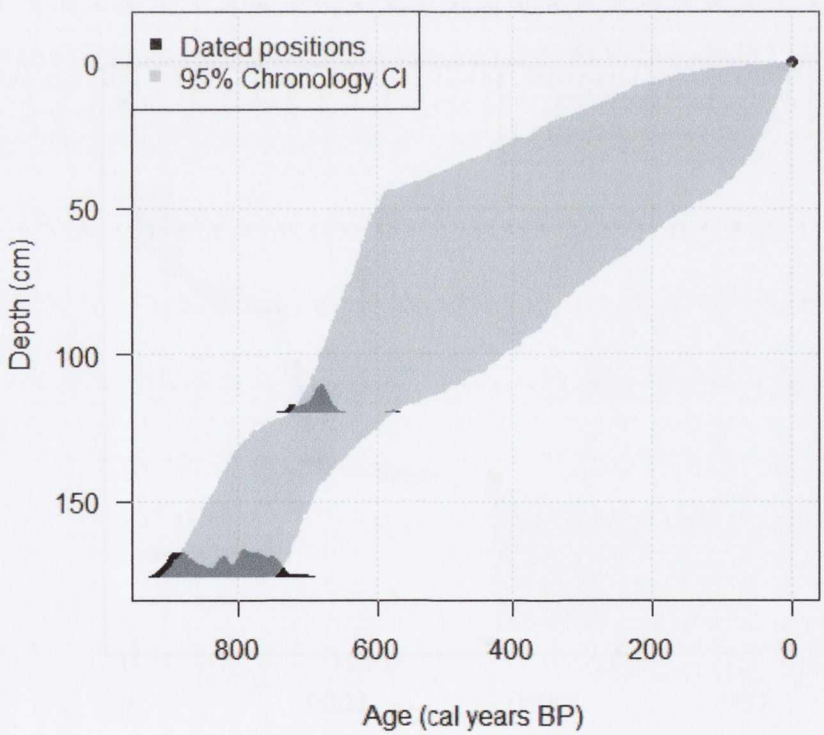


Figure 9.1.4 Chronology for Diheen Lough

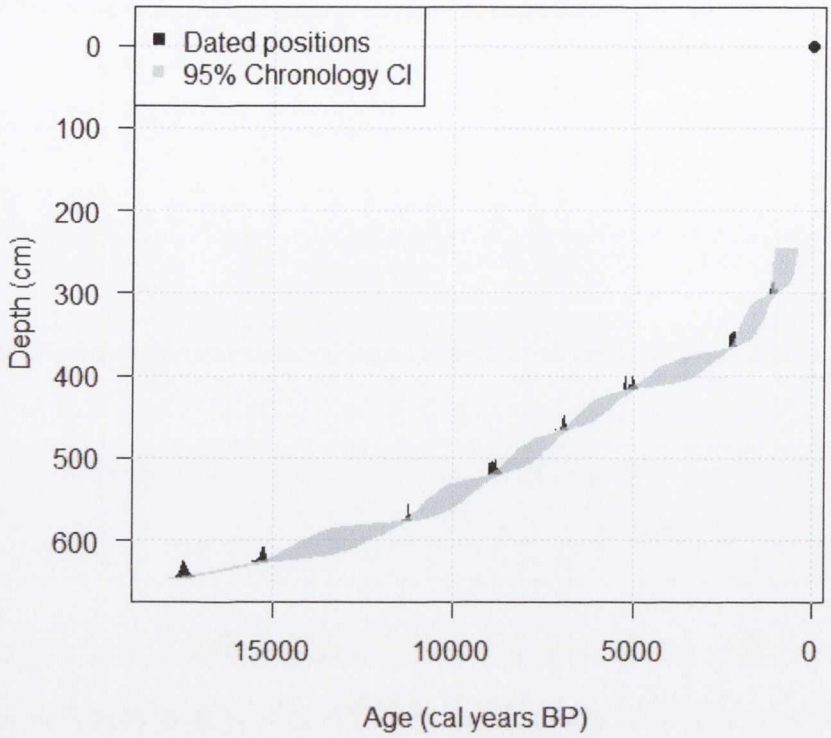


Figure 9.1.5 Chronology for Cuckoo Lough

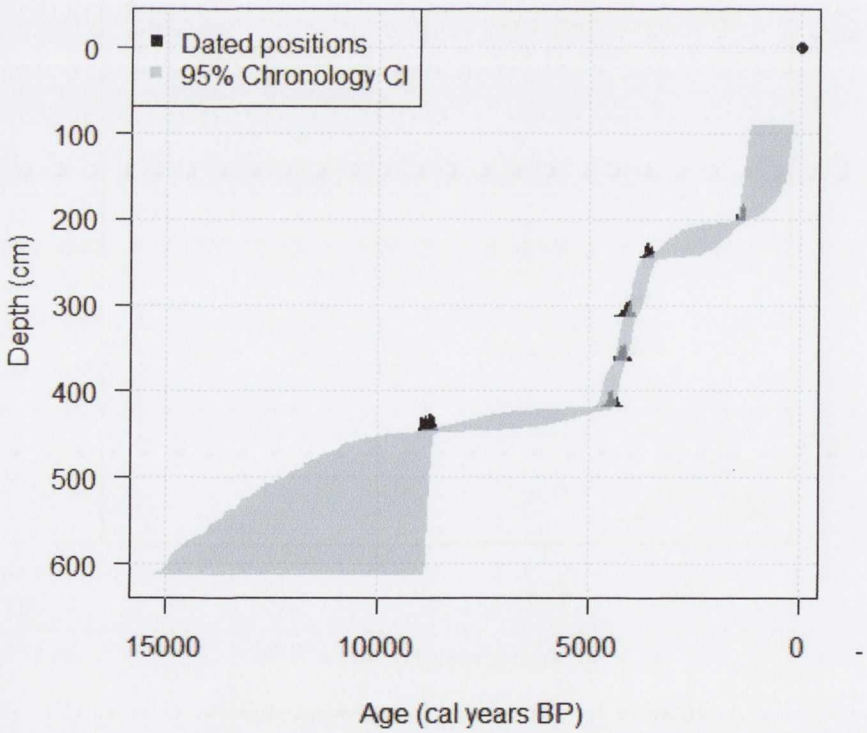


Figure 9.1.6 Chronology for Sheheree Lough

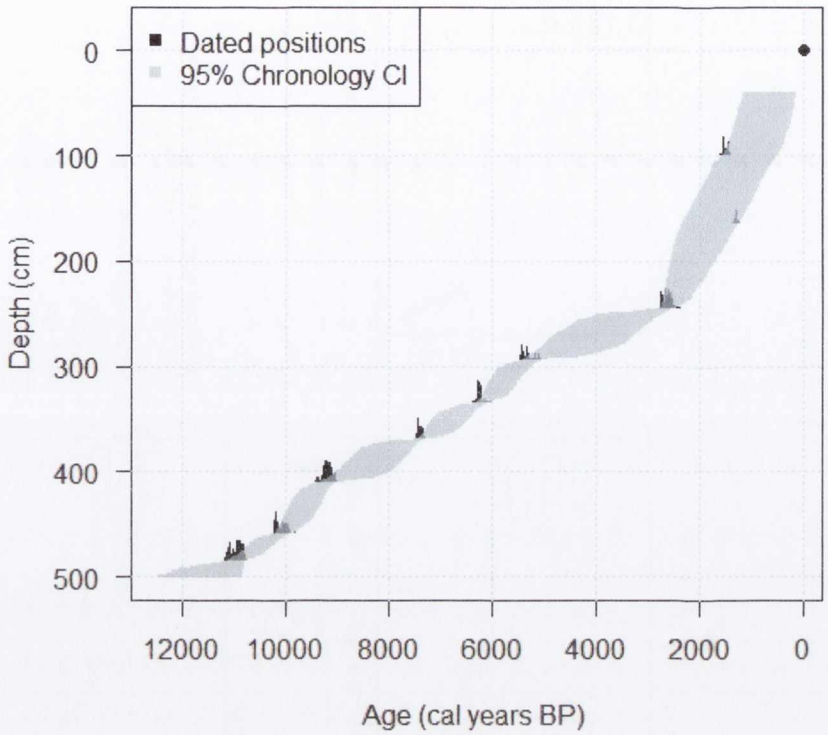


Figure 9.1.7 Chronology for Kelly's Lough

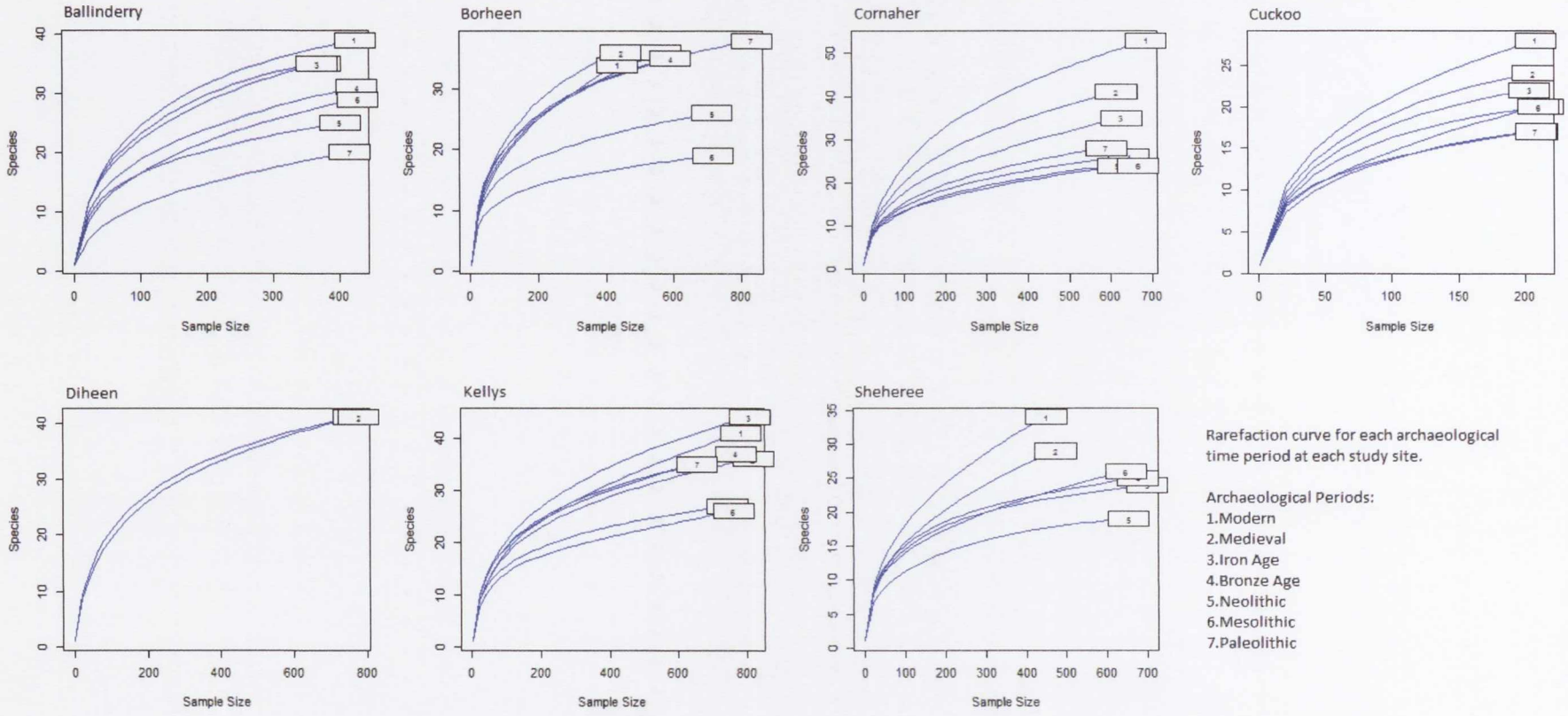


Figure 9.2 Rarefaction curves for each archaeological period at each study site.

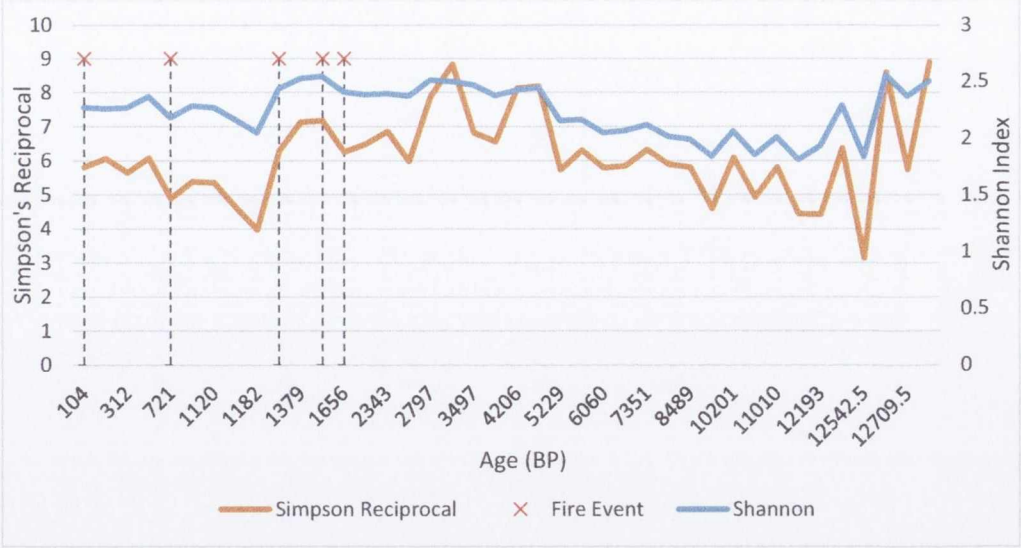


Figure 9.3.1 Borheen Lough fire events plotted with the Shannon and Simpson Indices over time, fire events with a magnitude greater than 100 pieces cm^{-2} $peak^{-1}$ are represented by black crosses, remaining fire events with a lower magnitude are represented by red crosses.

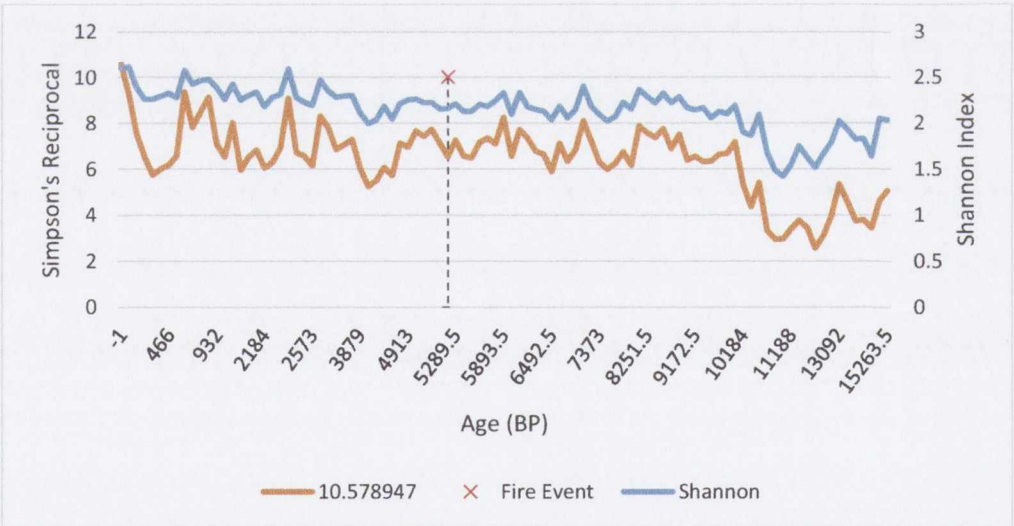


Figure 9.3.2 Cuckoo Lough fire events plotted with the Shannon and Simpson Indices over time, fire events with a magnitude greater than 100 pieces cm^{-2} $peak^{-1}$ are represented by black crosses, remaining fire events with a lower magnitude are represented by red crosses.

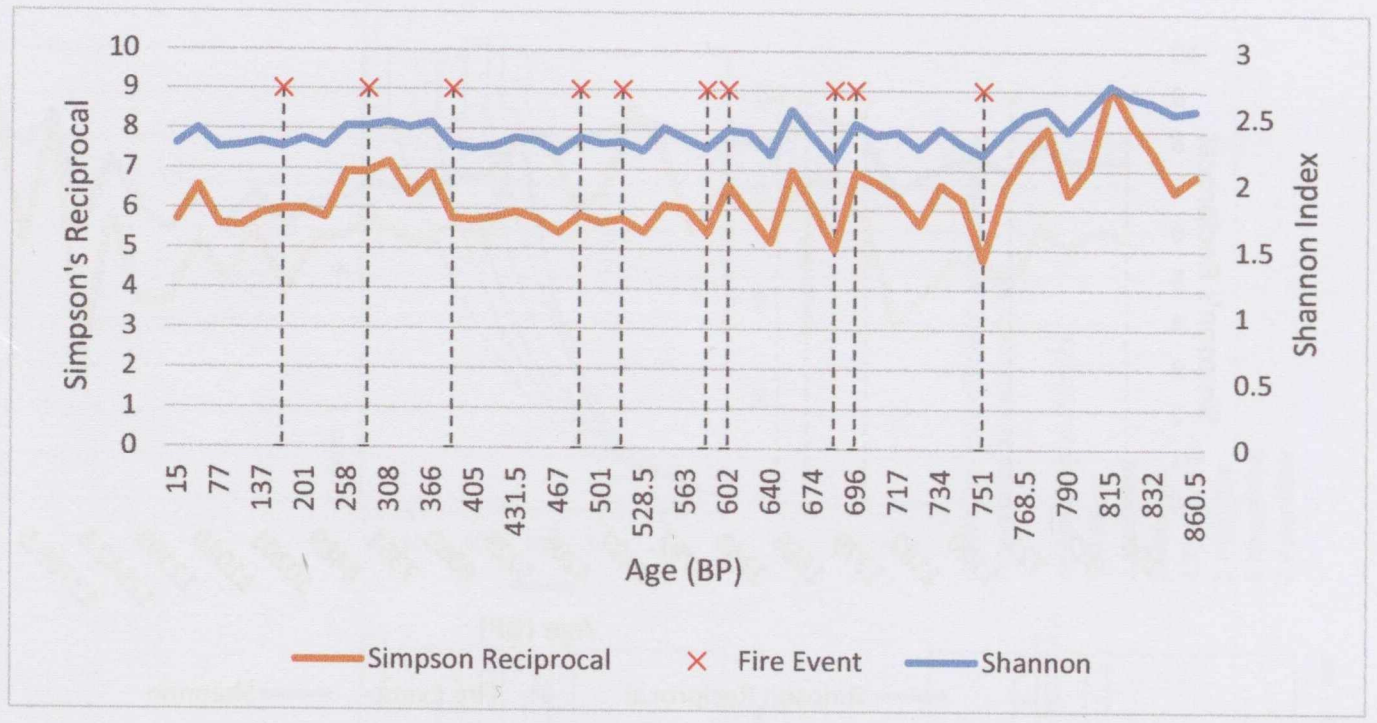


Figure 9.3.3 Diheen Lough fire events plotted with the Shannon and Simpson Indices over time, fire events with a magnitude greater than 100 pieces cm^{-2} $peak^{-1}$ are represented by black crosses, remaining fire events with a lower magnitude are represented by red crosses.

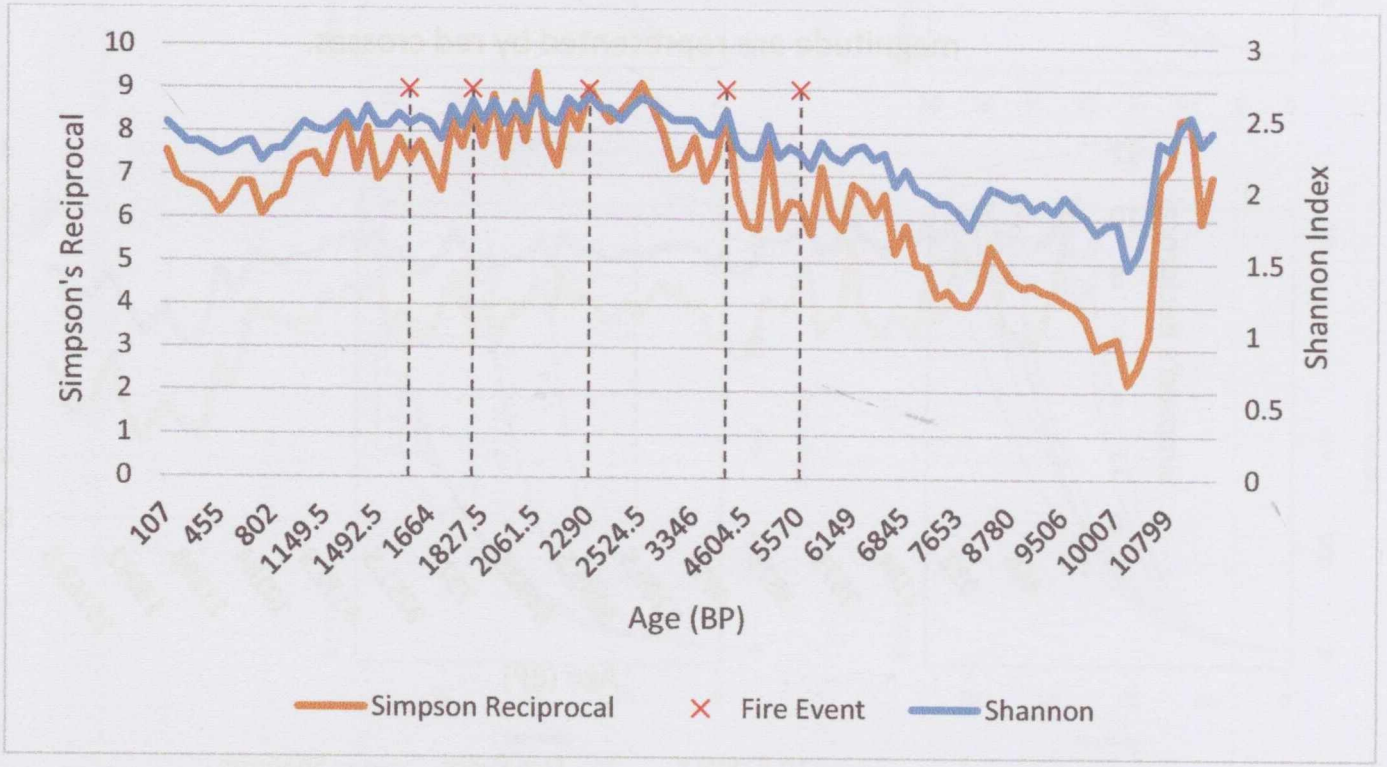


Figure 9.3.4 Kelly's Lough fire events plotted with the Shannon and Simpson Indices over time, fire events with a magnitude greater than 100 pieces cm^{-2} $peak^{-1}$ are represented by black crosses, remaining fire events with a lower magnitude are represented by red crosses