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Author(s)	McKeown, Michelle
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A Palaeolimnological Assessment of Human and Climate Influences on Chironomid Communities in Western Ireland

Michelle McKeown

Supervisor: Dr. Aaron Potito

Department of Geography
School of Geography and Archaeology
College of Arts, Social Sciences and Celtic Studies
National University of Ireland Galway

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ABSTRACT

Climate warming and biological response are prominent themes in Irish environmental research. It is widely acknowledged that certain species can be used as indicators of climate variables, and can be used to reconstruct environmental conditions spatially and temporally. The examination of ecological records to test the predictive response of certain species to climate change is ongoing and essential in the advancement of our understanding of global change. It is being increasingly recognised that chironomids (non-biting midge, Insecta; Diptera) are reliable indicators of summer temperatures. However, the breadth of palaeolimnological studies using chironomids to reconstruct temperature in Europe have tended to focus on high-latitude or high-altitude locations, or the late Glacial to early Holocene transition. It is not known if chironomids can reliably reconstruct Holocene temperature in less climatically-extreme locations such as Ireland. For the last 6,000 years, human influence has been a prominent feature on the Irish landscape and, as a result, lakes on the island are rarely isolated from such impacts. This study set out to test the sensitivity of chironomids to recent temperature and land-use change, and assess their potential as palaeotemperature indicators across various timescales.

In order to investigate climate change and human impacts on lakes in western Ireland, two main lines of enquiry were employed: the exploration of temperature data from a previously unexplored climate record in Markree Observatory (1842 to 2009), and chironomid-based palaeolimnological analysis. Results from the Markree reconstruction show the unique temperature regime for the County Sligo region, with Markree exhibiting characteristics of an 'inland' site despite its coastal location. As this record has been largely absent from past analyses of Ireland's long-term temperature trends, it helps to increase the spatial coverage of the extended Irish climate chronology. The newly reconstructed climate time-series for the study region allowed for greater accuracy in comparing recent temperature change with palaeolimnological changes through time. Chironomids were extracted from the centre of four different lakes. Three of these lakes were used to assess chironomid sensitivity to recent climate change and land-use histories through redundancy analysis and direct time-series comparisons with the Markree record and land-use records from the recent past. The chironomid communities from two of these lakes proved to be climatically sensitive, with chironomid-inferred temperatures following instrumental temperature trends, despite low impact human activities in the lake catchments. The chironomid community from the third lake was found to be more responsive to changes in lake level due to the presence of large, shallow shelves within the lake, which de-coupled the chironomid-temperature relationship. The fourth lake was used to investigate chironomid sensitivity to long-term Holocene climate fluctuations. This study is the first chironomid-based quantitative temperature reconstruction over the Holocene in Ireland. The temperature change inferred from this lake is largely in agreement with climate trends and events inferred from other palaeoclimate records in Europe and Ireland, including a Holocene Thermal Maximum at 9,600 cal. yr BP, a cooler trough between 7,800-7,500 cal. yr BP, mid-Holocene warmth peaking at 6,000 cal. yr BP, with subsequent cooling as Neoglacial conditions establish, with notable cooler phases between 4,000 and 3,600 cal. yr BP, and between 1,800 and 1,650 cal. yr BP. The overall findings of this study show the potential for chironomids to be used as palaeotemperate indicators across various timescales, and as a tool to tease apart human and climate impacts on Irish lakes through time.

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This thesis is dedicated to Kay and Teresa McKeown

AWARDS

2013	Arts Faculty Write-up Bursary. National University of Ireland, Galway.
2013	Best Postgraduate Paper at Irish Quaternary Research Association (IQUA) Annual Spring Meeting.
2013	Centre for Economic Development and Sustainability (CEDS) RSF Small Projects Award.
2012	Bill Watts 14CHRONO Award from Irish Quaternary Research Association (IQUA).
2011	Arts Faculty Travel Bursary to attend *Conference of Irish Geographers 2011* in Mary Immaculate College, Co. Limerick (May 6th – May 8th).
2011	Arts Faculty Travel Bursary/Geography Society funding to attend *Association of American Geographers Annual Meeting 2011* in Seattle, Washington, USA (April 12nd – 14th).
2010	Arts Faculty Travel Bursary/Geography Equipment Bursary and for field work expenses and radiometric dating sediment.
2009	Arts Faculty Travel Bursary to collect documentary evidence in Met Éireann, Dublin.

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DECLARATION OF ORIGINALITY

I, Michelle McKeown, declare that this thesis is entirely my own work.

Michelle McKeown

30/09/2013

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CHAPTER 1: INTRODUCTION

1.1 RATIONALE

As a mid-latitude country, Ireland's temperature has mirrored global temperature change quite closely. Mean annual temperature has increased by 0.7˚C since AD 1900, and global circulation models downscaled to the Irish Synoptic Station Network conclude that mean temperatures are forecasted to rise by 1.4˚C to 1.8˚C by the mid-21st century, and by 2˚C by the end of the 21st century (Sweeney *et al.*, 2008). Changes in species behaviour, ecosystem resilience and habitat distribution will likely occur as a result of the projected climate changes (Berry *et al*., 2002). Ireland's agricultural production systems, which accounts for one quarter of net foreign earnings and 8.6% of GDP (Hynes *et al.,* 2009), has been identified as a sector which will be negatively impacted by projected warming.

Ecosystems have to adapt to human encroachment and changing local and regional environmental conditions. Their ability to adapt may be overwhelmed by present and anticipated rates of global warming. Habitats are the fundamental building blocks for the environment, and living organisms residing in these ecosystems respond to altering climate regimes in different ways (Hossell *et al*., 2001). It is widely acknowledged that certain species can be used as indicators of climate, and can be used to reconstruct climate conditions across geographic regions and through time. The examination of ecological records to test the predictive response of certain species to climate change is ongoing and essential in the advancement of our understanding of global change.

Current understanding of past climate variability and climate modelling is often not sufficient to accurately project future climate trends (Knutti, 2008). While climate modelling has been very valuable in forecasting future climate change, one fundamental flaw is that the time period used to examine past climate change is quite short (Knutti, 2008). Climate forecasts are usually generated using instrumental data extending to the 1960s, as is the case for Irish forecasts (Sweeney, *et al*., 2008; McGrath *et al*., 2005). As past climates can be reconstructed using various proxies, palaeoclimate records can be used to extend records on climate parameters back hundreds and even thousands of years. This can place contemporary warming, and associated ecological response, in a greater climatic context. This palaeoclimate approach involves the identification of palaeo-indicators that are sensitive to a specific climate parameter. It is being increasingly recognised the chironomids (non-biting midge, Insecta; Diptera) are reliable indicators of past summer temperatures (Guo *et al*., 2013; Brooks *et al*., 2012; Porinchu *et al*., 2010, 2007; Axford *et al*., 2009). Therefore, chironomid communities can be used to extend the temperature record for Ireland than is presently available. Furthermore, chironomid assemblages can provide quantitative estimates of temperatures at high resolutions. However, the bulk of chironomid-temperature studies have tended to concentrate on high-elevation or high-latitude lakes, as these sites are known to be particularly responsive to climate change (Porinchu *et al*., 2010, 2007; Axford *et al*., 2009). Therefore, it is not known if chironomids can reliably reconstruct temperatures in less climatically extreme locations such as Ireland.

One way to gauge chironomid ability to register temperature change is to directly compare recent chironomid assemblages to known instrumental temperature change (Langdon *et al*., 2011; Porinchu *et al*., 2007; Larocque and Hall, 2003; Battarbee *et al.*, 2002; Cameron *et al*., 2002). To do this accurately, the instrumental datasets need to be long, continuous and homogenous, and chironomid assemblages need to be subsampled at a high temporal resolution. This technique can be used to determine the sensitivity of chironomids to fine-scale temperature change. Determining the correspondence between chironomid-based temperature inferences and instrumental records could also substantiate the applicability of chironomid assemblages for Holocene (11,700 cal. yr BP to present) temperature reconstructions in Ireland. Determining chironomid-inferred temperatures over centennial to millennial timescales can place recent warming in a much broader perspective. However, other environmental pressures, such as changing lake level, trophic status and pH, can de-couple the chironomid-temperature relationship (Velle *et al*., 2012, 2010b; Anderson *et al*., 2008). The impact of climate change and human influences on lake ecology is further complicated by the difficulty in isolating one from the other (Davidson and Jeppesen, 2013; Moss *et al*., 2011). This study will gauge chironomid community response to temperature in conjunction with human activities on three lakes in northwest Ireland over the recent past, and then examine the sensitivity of the chironomid community to broad fluctuations in temperature over the Holocene from a fourth lake in western Ireland.

1.2 AIMS AND OBJECTIVES

This first goal of this research is to establish chironomid response to known temperature change and human impacts over the recent past. Lake ecology was reconstructed over the last 150 years from three lake sites and compared to historical land-use change and recent climate change in order to tease apart a climate signal from more direct human influences. Currently available climate records in the northwest of Ireland only extend to 1960. To examine longer-term temperature patterns in the northwest of Ireland, this study extended the regional instrumental record by reconstructing and calibrating a previously unexplored dataset from Markree Observatory, County Sligo. This series was reconstructed back to 1842 using instrumental measurements contained in historical documents, making it one of the longest instrumental temperature records in Ireland. This ensured that a long-term homogenous temperature record was located in close proximity to the study lakes. The sensitivity of the chironomid-temperature relationship was evaluated through the reconstruction of high resolution chironomid-inferred temperature records from three lakes and compared to meteorological measurements from Markree Observatory. The lakes selected for this study are located in low- to mid-elevation sites with low to moderate human activity in the lake catchments. Therefore, human impacts on the lakes through time become another important component in the development of each lake. This study will not only test the sensitivity of chironomids in Ireland to recent temperature change but will also determine the degree to which direct human influences on these lakes are confounding the temperature signals, essentially assessing the resilience of chironomids to various human impacts.

The second goal of this research is to reconstruct summer temperatures throughout the Holocene from a fourth lake in order to capture longer term temperature fluctuations. This part of the study essentially tests the sensitivity of chironomids in Ireland to Holocene temperature change. Lough Nakeeroge is located in a remote coastal location in western Ireland with minimal historical human disturbance. This study will be the first to quantitatively reconstruct temperature change over the entire Holocene in Ireland. Recent studies have used chironomids to quantitatively reconstruct the abrupt shift in temperatures over the late Glacial to early Holocene transition on the island (Van Asch *et al.,* 2012; Watson *et al*., 2010). As Ireland is situated on the western edge of Europe and heavily influenced by north Atlantic oceanic regimes, a unique temperature history can be attained for this mid-latitude region. This can be compared to more northern latitude oceanic regions such as Greenland, Iceland and Norway in order to create a European-scale climate chronology. The overall aim of this study is to test the sensitivity of chironomids to temperature change in an Irish context and to assess their ability to be used as palaeotemperature indicators from decadal to millennial time scales.

1.3 THESIS STRUCTURE

Chapter two explores the theoretical background of this thesis in terms of four main themes. The first section explores climate change in Ireland over the recent past, focusing on the instrumental recording period. The second section explores the longer timescale of the Holocene and the studies that exist in an Irish context. The third section draws on the uniformitarian theory and the various biological indicators that can be used to reconstruct past environmental conditions with a focus on chironomid analysis as an innovative methodology. The final section elaborates on research that examines the complexities involved in using chironomids in temperature reconstructions. Finally, the chapter ends by introducing the four main research hypotheses for this dissertation.

Chapter three begins with a brief description of the study sites and the contemporary environment of each site. The chapter then discusses the application of fieldwork, laboratory work and statistical procedures used to collect and analyse the data. Chapter four is the first results chapter; it examines the instrumental record that was reconstructed from the Markree Observatory archives in County Sligo, northwest Ireland. This section focuses on maximum, minimum and mean temperatures to identify the magnitude of trends within the data series. A comparison with other long-term records in Ireland was carried out in order to situate the Markree series with existing records, allowing regional temperature variations to be recognised.

Chapters five, six and seven examines biological and physical variables contained within the sediment cores extracted from three lakes in northwest Ireland. Each lake will be discussed separately. These results chapters focus on reconstructing lake ecology through time and comparing chironomid community change with known historical human influences at each site. Quantitative estimates of temperature were inferred from chironomid data over the length of the core and compared with Markree average summer temperature (June, July and August) and average July temperatures. This was carried out in order to test the sensitivity of chironomids to recent temperature change in catchments with low to moderate human activities. This will broadly inform the sensitivity of chironomids to known temperature change in an Irish context, where most lake catchments contain at least a low human or agricultural presence.

Chapter eight is the final results chapter. A remote lake in western Ireland was selected to examine broad-scale temperature fluctuations over the entire Holocene. Human influence is minimal at this site due to its isolated location. The timescale under examination extends from 1,500 cal. yr BP to 10,350 cal. yr BP. This chapter places the recent temperature change evident in the chironomid models in a much broader context. Furthermore, this is the first attempt to reconstruct temperature change through the full Holocene in Ireland.

Chapter nine combines all of the results in a more comprehensive synthesis to examine chironomid community response to both climate change and human impacts in western Ireland. In doing so, it considers the meaning and significance of the findings with the existing literature. The research hypotheses laid out in chapter two are re-examined, incorporating findings from the dissertation. Finally, chapter ten contains conclusions that sums up the thesis findings and discusses a number of gaps that should be addressed in the future.

CHAPTER 2: THEORETICAL BACKGROUND AND RESEARCH HYPOTHESES

In this thesis, the sensitivity of chironomid assemblages to temperature change in Ireland is assessed across various timescales. First, a temperature record from Markree Observatory was reconstructed from 1842 to establish long-term temperature trends in the study area. This data, together with local land-use histories, was then compared to chironomid records from three lakes to establish dominant influences on the chironomid communities over the recent past. Finally, chironomid response to centennial- to millennial-scale temperature change was explored by comparing changes in chironomid assemblages to known regional temperature events through the Holocene. This chapter focuses on critically evaluating the literature that frames the theoretical background of this study.

2.1. IRISH CLIMATE

The climate of Ireland is characterised by mild moist winters and cool moist summers (Rohan, 1986). Recent July temperatures average at ~16°C, while average January temperatures are estimated at ~7°C (Met Éireann, 2013). Ireland is situated on the western edge of Europe bordering the Atlantic Ocean. The climate of Ireland is, therefore, dominated by the Atlantic Ocean and notable long-term periodicities are related to the North Atlantic Oscillation (NAO). It has been shown that air temperature, precipitation, cloud cover, wind velocity and relative humidity are all positively correlated to NAO index values (Jennings *et al.*, 2000). This mode of natural variability is most prevalent during the winter months (McElwain and Sweeney, 2003), and inter-decadal change is exhibited on irregular timescales (Hurrell and Deser, 2009; Hurrell, 1995). NAO variability and its influence on winter climate in Irish long-term records has been previously investigated (Galvin *et al*., 2011; McElwain and Sweeney, 2007). Due to the moderating influence of the Atlantic Ocean, coastal sites, especially in the west, experience more equable temperature regimes than inland localities (Smith, 1976). This includes suppressed diurnal ranges. In the middle and east of the island, temperatures tend to be somewhat more extreme. It has been suggested that, within 50 km of the coastline, the mean daily range of temperature is likely to be at least 1°C less than that of an inland location (Smith, 1976). However, topography also exerts a strong influence on local and regional climate. The complex interplay between topography and airstreams within the island results in some regions being more sheltered from the Atlantic Ocean, while others are exposed to the full effects of the ocean (Sweeney, 1997). Regional climate histories become important in order to understand the distinctive characteristics of Ireland's various climate regimes (Sweeney, 1997).

Mean global surface temperature has increased by 0.76˚C since the mid-19th century until 2005 (IPCC, 2007). Current trends in Irish temperature closely follow global patterns, with numerous studies having focused on climate amelioration at the beginning of the 20th century and the accelerated warming since the 1990s (McElwain and Sweeney, 2007, 2003; Vincent and Gullet, 1999; Zhai and Ren, 1999). Two main warm intervals have been widely acknowledged in Irish climate literature: 1910-1945 and 1978-present (McElwain and Sweeney, 2003). A cool period in the late 19th century is evident in the small number of available long instrumental records. However, these records show that, despite low temperatures in the 1880s, a general warming trend takes place leading up to the 20th century. As the late 19th century warming has received little attention, it is important to establish a longer baseline against which present and future warming can be compared (Butler *et al*., 2005). To date, studies have shown that winter warming accounts for most of the recent annual warming in Ireland (Jones *et al.*, 2001), with maximum temperatures accounting for the majority of this change (McElwain and Sweeney, 2003; Sweeney *et al.*, 2002). It has also been shown that the majority of warming in the other three seasons is driven by minimum temperatures increasing at around twice the rate of maximum temperatures (McElwain and Sweeney, 2007; Vincent and Gullet, 1999; Zhai and Ren, 1999), possibly due to increasing cloud cover (Kiely *et al.*, 2007).

2.1.1 The Recent Past and Instrumental Records

Humans have recorded climate histories over the last few centuries both qualitatively (documentary evidence) and quantitatively (instrumental measurements). Modern climatologists rely on continuous meteorological measurements using instruments to infer a climate history. However, climatologists struggle to piece together a continuous climate chronology from the instrumental record before 1900. Although the general consensus is that temperatures are increasing, the instrumental period is limited to the 20th century in most countries. Reliable longer-term instrumental records are globally rare, with only about 50 climate stations worldwide offering greater than 200 years of continuous temperature data (Bradley, 1991). Of the climate records that extend into the 19th century, the vast majority are found in Europe (Butler *et al*., 2005). Consequently, for much of the globe, the spatially complete instrumental period is quite short (Klingbjer and Moberg, 2003), limiting the time-scale involved in climate research. Climate data in Ireland, before the establishment of the Irish Meteorological Service in 1936, is largely dependent on the instrumental data collected by scientific institutions and private landowners. In Ireland a small number of stations actively recorded meteorological parameters prior to the 20th century, and only one station (Armagh Observatory) has a record accurately extending back to the late 18th century. The majority of meteorological stations in Ireland only began recording continuously in the 1950s and 1960s (McElwain and Sweeney, 2007), so the remaining long-term climate records provide an extended insight into climate trends in Ireland.

In recent studies of climate change in Ireland, it has been common practice to utilise data from the 1950s/1960s to present as meteorological information is more assessable from this time, particularly where climate modelling is concerned (Charlton *et al.*, 2006; Kiely, 1999; Hulme *et al.*, 1995). This is a rather short observational time period, especially when climate forecasting is used. One way to overcome this problem is to examine longer climate records. A number of studies have created national- and continental-scale long-term datasets by combining data from numerous stations to create composite records of climate change (Klingbjer and Moberg, 2003; Manley, 1974). While this is ideal for investigating climatic trends over large areas, details regarding more localised climate patterns, such as those exhibited in the longer Irish records, are lost. According to Donnelly *et al*. (2004), an understanding of climate at the regional and local scale is imperative to adequately examine potential impacts of future climate change. Although a number of studies have examined climate fluctuations at a regional Irish scale (McElwain and Sweeney, 2007, 2003; Butler *et al*., 2005; Sweeney *et al*., 2002; Butler, 1994), geographic coverage of Ireland is not complete**.** The Markree Observatory record, located in the north-western region of Ireland, extends back to 1842, and is one of the longest instrumental temperature records in Ireland. Despite its length, this record has been largely absent from past analyses of Ireland's long-term temperature trends, rendering spatial coverage for the extended Irish climate chronology incomplete. Therefore, the Markree climate series is important as it provides an extended insight into the regional climate of the northwest of Ireland which is presently unexplored.

Although the introduction of a new long-term temperature series offers an extended regional chronology, most historic instrumental records do suffer from a degree of imperfection in portions of the series (Butler *et al*., 2005). Records must conform to a number of criteria in order to adequately narrate a climate story. These include: (1) continuity of data; (2) knowledge of instrumentation, exposure of instruments and time of observations; and (3) knowledge of site changes, such as vegetation alterations and urban encroachment, which may affect microclimate. The majority of meteorological records lack one or more of these criteria, making the climate reconstruction inadequate. To date in Ireland only a small number of temperature series that fill these absolute rules (Butler *et al.,* 2005). Markree is one such record.

2.1.2 Holocene Climate

A comprehensive understanding of Holocene climate variability offers a broader perspective for studying trends in recent climate change. Although the abrupt climate shifts at the end of the last Glacial period have received considerable attention (Van Asch *et al.,* 2012; Watson *et al*., 2010; Langdon *et al*., 2010b; Caseldine *et al*., 2006; Brooks and Birks, 2002; 2000), a general picture of Holocene climate in the Northern Hemisphere is also emerging (Larocque-Tobler *et al*., 2012; Langdon *et al*., 2010b; Edwards *et al*., 2007; Axford *et al*., 2007; Mayewski *et al.,* 2004). In Europe, palaeoclimate studies over the full Holocene have tended to focus on high latitude and high altitude regions. This highlights the spatial inconsistency in the geographic spread of palaeoclimate studies over this time period. Gaps in the palaeoclimate chronology need to be addressed in order to gain a more comprehensive understanding of the magnitude and timing of cooling and warming episodes across Europe.

Chironomid-inferred temperature reconstructions from Northern Sweden (Larocque and Hall, 2003), Finnish Lapland (Seppä *et al*., 2002), Fennoscandia (Korhola *et al*., 2002a, 2002b), Swiss Alps (Heiri *et al.*, 2003) and Greenland (Schmidt *et al*., 2011) show a more or less decreasing trend in temperature from ~9,000 cal. yr BP to present. These studies have further shown that temperatures were higher during the early and mid-Holocene (11,000 cal. yr BP to 4,000 cal. yr BP) and slightly cooler during the late Holocene, which spans ~3,500 cal. yr BP to ~1,000 cal. yr BP (Schmidt *et al*., 2011; Mayewski *et al*., 2004; Larocque and Hall, 2004; Heiri *et al*., 2003; Seppä *et al*., 2002; Korhola *et al*., 2000b). The timing of peak Holocene warmth is spatially variable (Kaufman *et al*., 2004). Studies undertaken in northern Sweden (Laroque and Hall, 2003), Kola Peninsula (Ilyashuk *et al*., 2005) and the eastern Alps in Austria (Ilyashuk *et al*., 2011) indicate that the Holocene Thermal Maximum (HTM) occurred between 10,000 and 9,000 cal. yr BP. However, other sites in northern and central Fennoscandia (Velle *et al*., 2005; Seppä *et al*., 2002; Rosén *et al*., 2001), northern Iceland (Caseldine *et al*., 2006) and Scotland (Edwards *et al*., 2007) suggest that the HTM was not reached until around 8,000 to 7,000 cal. yr BP.

It is clear that the timing of peak early Holocene warmth varies spatially (Kaufman *et al*., 2004). However, the magnitude of early Holocene thermal warmth appears to have been broadly similar in magnitude across northwestern European and sub-Arctic regions (Langdon *et al*., 2010b). Larocque and Hall (2004) suggest that early Holocene temperatures were around 2.5˚C to 3˚C warmer than today in northern Sweden. Ilyashuk *et al*. (2005) supports this finding with results from the Kola Penninsula. Chironomid-inferred temperatures from northern Fennoscandia suggest that temperatures in the early Holocene were between 1˚C and 2˚C warmer than present (Velle *et al*., 2005; Seppä *et al*., 2002; Rosén *et al*., 2001). The general summer warmth of the early Holocene in northwestern Europe and the north Atlantic coincides with insolation at 65˚N being at its Holocene maximum (Langdon *et al*., 2010b).

Widespread cooling after early Holocene warming is a feature in most Holocene temperature studies in Europe. This cooling has been suggested to last between 9,000 to 8,000 cal. yr BP in northern European latitudes, and has been a focus of much research in Europe (Langdon *et al*., 2010b; Edwards *et al*., 2007; Head *et al*., 2007; Caseldine *et al*., 2006; Rohling and Pälike, 2005). It is a unique phase in the Holocene time period as this cooling occurs at a time when large Northern

Hemisphere ice sheets were still present (Mayewski *et al*., 2004). Within this cool period, there is an abrupt cooling event ~8,200 cal. yr BP (Alley *et al.,* 1997). The '8,200 year event" is commonly regarded as the most significant Holocene cooling episode, with a clear signature in the Greenland ice core (Alley *et al*., 1997). This cooler period is evident over much of the Northern Hemisphere due to large-scale strengthening of atmospheric circulation over the North Atlantic, and an increase in the frequency of winter westerly wind regimes (Mayewski *et al.,* 2004). Mountain glaciers and northern latitude ice sheets advanced in the Northern Hemisphere. However, the timing of this prolonged cool period has been identified as occurring much later in lower latitude locations. Head *et al*. (2007) and Edwards *et al*. (2007) identified a 320 yr prolonged cool period in western Ireland and Scotland from 7,790 cal. yr BP to 7,470 cal. yr BP, where temperatures were identified as declining by ~1˚C. A similar change in temperatures, along with a decline in woodland, has been identified in the Swiss Alps at around 7,800 cal. yr BP (Heiri *et al*., 2003).

Quantitative temperature reconstructions in Europe suggest that temperatures were warm and stable between 7,000 cal. yr BP and 5,800 cal. yr BP (Velle *et al*., 2005; Davis *et al*., 2003; Korhola *et al*., 2002b). Davis *et al.* (2003) suggest that temperatures in northwest Europe were highest around 6,000 cal. yr BP. Velle *et al* (2005) argue that blocking anticyclones over northern Scandinavia resulted in westerly winds being replaced by more southerly winds, bringing warmer conditions to western Europe. In Ireland, Stolze *et al*. (2012) linked human settlement to a period of warmer summers with reduced rainfall between 5,800 to 5,550 cal. yr BP. A number of palynological records from western Ireland broadly suggest climate amelioration between 6,000 cal. yr BP and 5,600 cal. yr BP in line with an increase in human activities (Stolze, 2013; Verrill and Tipping, 2010). This period has been the focus of a number of archaeological and palaeoenvironmental studies in Ireland and is known as the Early Neolithic. Studies in Ireland have focused on the rapid increase in human activities on the landscape, with inferences to climate made with evidence from pollen records (Stolze, 2013; 2012; Taylor *et al*., 2013; Cooney, 2007; O'Connell and Molloy, 2001). However, no quantitative temperature estimates are available to support these studies. This study will be the first to broadly infer temperature estimates over this period.

Following general mid-Holocene warmth, numerous studies show late Holocene cooling as Neoglacial conditions establish (Korhola *et al.*, 2002b; Seppä and Birks, 2002; Rosén *et al.*, 2001). Human impacts in western Ireland declined between 5,600 and 4,500 cal. yr BP, a period that has been associated with climate deterioration (Stolze *et al*., 2013; 2012; Caseldine *et al*., 2005). Korhola *et al*. (2002) identified a pronounced climate cooling around 5,800 cal. yr BP in northern Fennoscandia, using chironomid-inferred temperatures. This temperature decline is further supported by maritime glacier fluctuations in western Norway, which suggest cold/dry conditions after ~6,000 cal. yr BP (Nesje *et al.,* 2001). Evidence for decreased temperatures between ~4,200 cal. yr BP and ~3,600 cal. yr BP is found in numerous European records, from Austrian Alps (Ilyashuk *et al*., 2011), southern Sweden (Jessen *et al*., 2005) and western Norway (Nesje *et al.,* 2001). Literature focusing on the Neoglacial in Europe has claimed that a strong relationship exists between low solar irradiance and reduced temperatures (Hormes *et al.*, 2006; Koch and Clague, 2006; Holzhauser *et al*., 2005; Maasch *et al*., 2005; Karlén and Kuylenstierna, 1996). This cooling instigated growth in mountain glaciers (Matthews and Dresser, 2008; Seierstad *et al*., 2002; Nesje *et al.,* 2001) and the retreat of treeline (Barrett *et al*., 2001; Dahl and Nesje, 1996).

Pollen records from Ireland have identified large-scale woodland regeneration between ~1,750 cal. yr BP and ~1,450 cal. yr BP, which has been linked to a decline in farming activities (Newman *et al*., 2007; Molloy and O'Connell, 2004; O'Connell, 1994). This period is widely recognised as the Iron Age Lull. It is not known if this phenomenon was culturally or climatically driven. Tree-ring records from Ireland have shown a rapid change in environmental conditions between 1,743 cal. yr BP and 1,450 cal. yr BP (Baillie and Munroe, 1988). In northern Fennoscandia an abrupt cold event was identified at 1,800 cal. yr BP using a chironomid-inferred temperature reconstruction (Korhola *et al*., 2002b). As Iron Age temperature change in Ireland is largely unknown, chironomid analysis may be able to provide an insight into summer temperatures at this time.

2.2 PALAEOECOLOGY AND PALAEOCLIMATOLOGY

The primary goal of palaeoecology is to reconstruct the past from fossil evidence. The principle of uniformitarianism, derived by Charles Lyell, states that the present is the key to the past (Rull, 2010) and, therefore, the key to the future. Palaeoenvironmental proxies can be used to reconstruct the physical environment of the past through the application of contemporary knowledge on taxa ecology. An increasing number of palaeoecological studies have been undertaken in recent years using various biological and chemical proxies to reconstruct different aspects of the environment in unique ways. Palaeolimnological (lake history) techniques can provide a powerful tool to reconstruct the past and determine the effects of environmental alterations on freshwater ecosystems. It is widely accepted that lakes are excellent archives of past environmental conditions (Adrian *et al*., 2009; Porinchu *et al*., 2003; Schindler, 2001; Battarbee, 2000). Temperature, salinity, pH, nutrient status, productivity and lake level changes through time can be traced through particular proxies, and the magnitude of such changes can be determined over various timescales (Smol, 2005, 1992). However, the efficiency of different indicators is affected by various local environmental and in-lake pressures, in addition to climate change (Adrian *et al*., 2009). This emphasises the need for a greater understanding of the complex interactions between different palaeolimnological proxies and various influencing variables. Thus, specific proxies may be better suited for inferring particular environmental variables, such as temperature, precipitation, salinity, pH or oxygen concentrations. The power of a specific palaeolimnolgical proxy for accurately deriving the variable of interest can also vary across geographical regions, between different lake types and through time (Battarbee, 2000).

It is recognised that modern climate warming is one of the most severe threats to ecosystems worldwide (Adrian *et al*., 2009; Rosenzweig *et al*., 2008; Wolfgang *et al*., 2001). As a result, interest in how climate can alter biological, chemical and physical components in an ecosystem has increased. Species sensitive to environmental alterations, either directly or indirectly attributed to climate shifts (Walther *et al*. 2002; McCarthy, 2001; Hughes, 2000), can alter ecosystem dynamics through changes in physiochemical and biotic controls (Langdon *et al*., 2010a; Adrian *et al*., 2009). Therefore, investigating how ecosystems are reacting to current climate pressures allows an insight into how they may have responded in the past, and how they might behave in the future. Palaeolimnological approaches using thermally-sensitive species to infer past temperature conditions can provide sub-decadal to millennial scale temperature reconstructions. As lakes are widely distributed over the globe, they can act as reservoirs of environmental information in different geographic locations, in turn allowing regional climate signatures to be captured in their sediment sequences (Adrian *et al*., 2009; Smol and Cummin, 2000). Therefore, palaeolimnological records in particular have been pivotal in the development of more elaborative climate records, allowing a more intricate understanding of climate change and its impact on lake ecosystems (Leavitt *et al*., 2009; Smol and Cumming 2008). With the development of modern methods for dating sediment by ^{210}Pb and ^{14}C, palaeolimnological techniques for inferring climate conditions to specific time periods has improved greatly.

The relevance of a particular proxy indicator to infer a specific climate variable can be dependent on the characteristics of the lake from which it is derived (Adrian *et al*., 2009). These characteristics can be described as the physical structure of the lake (bathymetry), lake chemistry and food-web interactions (Adrian *et al*., 2009). Therefore, certain lakes may be better suited to climate analysis due to the simplicity of their chemical, biological and physical structure. The task of isolating climate change from other confounding environmental variables can still be a difficult task, particularly when undertaking climate reconstructions over long time periods. Here, as lake conditions can also change over time independently of climate. Hence, caution should always be exercised when interpreting proxy assemblages. The need to separate climate signals from other environmental variables, both human-induced and natural, is becoming increasingly important in research spanning the Holocene, and especially over the more recent industrialised era. In order to determine if a thermally-sensitive proxy is registering the desired temperature signal independent of other in-lake conditions, a comparison with known temperature records can be carried out, as is done in this study.

2.3 PALAEOCLIMATOLOGY IN IRELAND

As Ireland is situated on the western fringe of Europe and exposed to the full extent of the Atlantic Ocean, the island is in an ideal location to reconstruct regional climate fluctuations and events over the Holocene. Irish palaeoecological research on climate and environmental change has tended to focus on pollen, tree rings and diatoms, with a small number recently examining chironomids. The tree-ring chronology for Irish Oak extends back over 7,000 years and shows notable downturns in growth relating to climatic events (Baillie and Munro, 1988; Pilcher *et al*., 1984; Briffa *et al*., 1983). Climate information can be derived at a high resolution as tree-ring widths respond annually to both precipitation and temperature. Despite this advantage, dendroclimatology is more difficult in an Irish context as no species on the island is growing at the maximum extent of their latitudinal limit (Galvin, 2010), the ideal situation for trees to respond to climatological variables. Furthermore, competition between species, insect attack and animal grazing can all have an impact on tree growth. Such confounding factors can complicate the detection of a climate signal.

Pollen found in bog and lake sediments has the potential to be used for palaeoclimate studies, providing a broader period to investigate human impacts and track climate change through vegetation patterns. In Ireland, most pollen studies have been used to reconstruct woodland recovery since the last ice-age (O'Connell *et al*., 1988; Bradshaw and Browne, 1987; Jessen, 1949). This research has tended to steer towards human impacts on the landscape over the Holocene (Ghilardi and O'Connell, 2013; Caseldine *et al*., 2007; Edwards *et al*., 2007; Molloy and O'Connell, 2007; Mitchell, 2006; Caseldine *et al*., 2005; Molloy and O'Connell, 2004; Huang, 2002; O'Connell and Molloy, 2005; Jeličič and O'Connell, 2001; Molloy and O'Connell, 1995, 1991; Edwards, 1985; Lynch 1981). While Irish pollen research has revealed the important relationship between landscape modification and human impacts in Ireland, little work has been carried out on climate fluctuations over the Holocene on the island. The few pollen studies that have investigated Holocene climate have been carried out at a high resolution over narrow timescales and have shown a number of climate events including; 5,200-5,100 cal. yr BP, believed to be linked to increased storm activity (Caseldine *et al*., 2005); the 4,200 cal. yr BP event, which has been linked to wetter conditions (Swindle *et al*., 2012) and the 8,200 cal. yr BP cold event (Ghilardi and O'Connell, 2013; Head *et al*., 2007). Broad-scale temperature fluctuations over the Holocene remain poorly understood in Ireland.

Despite the many advantages that pollen can offer palaeoecological studies, the response of terrestrial vegetation to climate shifts may take centuries to adjust fully. Therefore, pollen rarely provides high resolution decadal to sub-centennial scale climate estimates. Consequently, fine-scale or low magnitude climate fluctuations may not be captured. As pollen and tree-rings respond to temperature and precipitation, the hydrological component cannot be easily separated from the thermal as vegetation response to effective moisture can, at times, confound the temperature signal. Palaeoindicators that can infer a single parameter such as temperature can reveal more information than biological proxies that respond to two or more climate variables. Chironomids have been shown to accurately infer temperature independent of other meteorological parameters. Furthermore, chironomids can be examined across geographically-diverse regions and at a high temporal resolution to reconstruct temperature regimes at sub-decadal to centennial and millennial scales. However, current chironomid research in Ireland is restricted to temperature reconstructions over the late Glacial to early Holocene transition (van Asch *et al*., 2012; Turner *et al*., 2010; Watson *et al*., 2010; Lutz, 2009), where chironomids have been shown to respond to high magnitude climate shifts. There is a notable lack of palaeoenvironmental indicators employed in Irish Holocene temperature studies.

2.4 CHIRONOMIDS

The fossilised remains from various organisms embedded in the sediment of lakes are an ideal source for environmental information as they provide a continuous record of changes within the ecosystem through time (Eggermont and Heiri, 2011; Battarbee, 1991; Smol *et al.,* 1991). Chironomids are now regarded as one of the most promising biological indicators to quantitatively infer temperature (Larocque-Tobler *et al.*, 2012; Porinchu *et al.,* 2010; Brooks, 2006; Walker and Cwynar, 2006; Brooks and Birks, 2000; Lotter *et al*., 1997; Olander *et al*., 1997; Walker *et al*., 1997, 1991). Chironomids represent 20% of all freshwater insects in lake systems and they dominate the profundal zone (Lutz, 2009). Furthermore, they are important components in lake ecosystems due to their high abundance and species diversity. In recent years they have been increasingly used in palaeolimnological research due to the species' ability to rapidly register environmental changes. This family can tolerate a wide range of environmental pressures, including changes in pH, oxygen concentration, temperature, trophic status, salinity, depth, lake chemistry and macrophyte abundance. Some taxa have narrow ecological limits for specific environmental pressures. However, a large number of taxa have quite broad ecological preferences, making the specialist species invaluable in palaeo-reconstructions. Head capsules of the chironomid larvae are chitinous, allowing them to remain preserved in lakes sediments (Hoffmann, 1986) where they can be easily extracted and identified. Over the last decade, chironomid fossil identification has improved greatly, where taxa can be accurately identified to genus and even species level (Brooks *et al*., 2007; Walker, 2007). Hence, more refined environmental information can now be inferred from chironomid community composition.

In early research, chironomids were used by biologists as indicators of lake water quality (Whiteside, 1983; Thienmann, 1926; Naumann, 1919). Despite the important contribution to chironomid research that was made by these early scientists, the importance of climate as a potential driver in chironomid community change was neglected. In recent decades, chironomids have become widely utilised to reconstruct temperature through time (Larocque-Tobler *et al.*, 2012; Self *et al*., 2011; Velle *et al*., 2010b; Langdon *et al*., 2010b; Axford *et al*., 2009; Edwards *et al*., 2007; Porinchu *et al*., 2007, 2003; Potito *et al*., 2006; Walker *et al*., 1991). Chironomids can provide quantitative estimates of surface water and/air temperatures with the aid of numerical chironomid-based inference models (transfer functions). Temperature reconstructions rely on the sensitivity of chironomid assemblages to air and/or lake surface water temperature. Regional training sets investigate the empirical relationship between recently-deposited chironomid taxa with modern environmental variables in order to determine dominant environmental controls (Potito, forthcoming; Holmes *et al.*, 2009; Barley *et al.*, 2006; Heiri and Lotter, 2003; Larocque *et al*., 2001). In the development of training sets it is usual to include several different types of lakes geographically spread apart in order to get a broad range of variables that can influence local chironomid assemblages (Eggermont and Heiri, 2012). Studies have widely shown temperature to be the most important variable explaining the distribution of chironomid species through most regions (Eggermont and Heiri, 2012; Brooks *et al*., 2012).

Numerous studies have constructed unique training sets to accommodate regional variations in chironomid communities. Chironomid-based temperature inference models have been shown to outperform other models designed to infer different environmental variables (Brooks *et al*., 2012) such as lake depth (Korhola *et al*., 2000a), dissolved organic carbon (DOC) (Larocque *et al*., 2006), chlorophyll *a* (Brodersen and Lindegaard, 1999), dissolved oxygen (Quinlan and Smol, 2001), total phosphorus (Langdon *et al*., 2006; Brooks *et al*., 2001) and total nitrogen (Brodersen and Anderson, 2002). This emphasises the dominant influence temperature has on the distribution of chironomid species compared to other environmental variables. Inference models are particularly useful when using a multi-site approach as it is difficult to correlate chironomid stratigraphies between lakes due to the fact that climate change can be captured uniquely in different chironomid assemblages. In an Irish context, summer air temperature has been found to be the dominant environmental control across lake types in western Ireland (R^2_{jack} = 0.60, RMSEP = 0.51) (Potito *et al*., forthcoming).

2.4.1 Chironomids and Holocene Climate Change

It has been widely shown that chironomids can register high amplitude temperature shifts over the late Glacial and early Holocene period, when the climate began to warm rapidly (van Asch *et al*., 2012; Watson *et al.*, 2010; Larocque and Finsinger, 2008; Bedford *et al*., 2004; Heiri *et al*., 2003; Brooks and Birks, 2001, 2000; Birks *et al*, 2000; Brooks, 2000; Cwynar and Levesque, 1995; Walker *et al*., 1992; Walker and Mathewes, 1989). However, studies using chironomid-based approaches have also provided detailed evidence of notable summer temperature fluctuations over the entire Holocene (Clegg *et al*., 2010; Laroque *et al*., 2010; Axford *et al*., 2009; Heiri *et al*., 2007; Caseldine *et al*., 2006; Heiri and Millet, 2005; Heiri *et al*., 2003). Such climate oscillations have been captured using chironomid-temperature inference models. Here, trends are largely in agreement with other important records such as the Greenland ice cores. In spite of the recent progress in Holocene research using chironomids, geographic coverage needs to be expanded as various regions will display different temperature trajectories and rates of change.

Although chironomid communities can be influenced by other complicating factors (Velle *et al*., 2012, 2010a; Anderson *et al*., 2008; Brooks, 2006; Heiri and Lotter, 2005, 2003), overall temperature is still the strongest variable explaining species turnover throughout the Holocene, despite natural changes in lake pH, trophic status and depth (Axford *et al*., 2009; Caseldine *et al*., 2006; Brooks, 2003). This emphasises the resilience chironomids have to changes in natural in-lake variables over long time periods. However, it can be difficult to reconstruct temperatures when intense periods of human activity have dominated the catchment (Heiri and Lotter, 2003). Abrupt changes in lake conditions can decouple the chironomid-temperature relationship. This has been well-documented in research on chemical contamination and nutrient loading in lakes from human-induced pressures on the landscape (Taylor *et al*., 2013; Gathorne-Hardy *et al*., 2009, 2007; Heiri and Lotter, 2005, 2003). This demonstrates that, when human interference with a lake system exceeds a certain threshold, the influence of temperature on chironomid taxa can be compromised.

2.4.2 Chironomids and 20th Century Climate Change

The majority of chironomid-based temperature reconstructions have tended to focus on long-term centennial to millenennial-scale changes. A small number of studies have examined recent temperature change over the instrumental period at decadal and sub-decadal scales in order to detect how chironomid species are responding to modern warming (Guo *et al*., 2013; Porinchu *et al*., 2010; Solovieva *et al*., 2005; Battarbee *et al*., 2002; Cameron *et al*., 2002; Clerk *et al*., 2000; Livingstone and Lotter, 1998). Investigating chironomid community turnover over the 20th century can provide an important insight into past climate regimes and ecological responses. However, biological proxies embedded in the sediments of lakes are rarely used to investigate recent climate change (Laroque-Tobler *et al.*, 2012). The studies that have been carried out have tended to focus on regions situated in either high latitudes or high altitudes as these are the areas experiencing rapid warming over the recent past (Guo *et al*., 2013; Porinchu *et al*., 2010; Laroque *et al*., 2009; Battarbee *et al*., 2002; Cameron *et al*., 2002; Livingstone and Lotter, 1998). Chironomid communities in such locations are known to be highly sensitive to temperature change (Laroque *et al*., 2009; Porinchu *et al*., 2010; Battarbee *et al*., 2002), while little research has been carried out in less extreme locations where recent warming trends are more muted. The potential to explore the chironomid-temperature relationship in lower altitude and lower latitude sites exists, and our understanding of chironomid sensitivity to temperatures can be further refined.

In high-elevation and high-latitude lakes, the physical, chemical and biological characteristics can be directly and indirectly influenced by climate change. This, in turn, may increase lake productivity through longer ice-free seasons and, for example, potentially introduce invasive species affecting biodiversity and ecosystem dynamics (Porinchu *et al*., 2009; Holzapfel and Vinebrooke, 2005; Saros *et al*., 2003). Mid-latitude, low elevation lakes that do not experience a recurring ice season can be influenced by different environmental-climate pressures and an understanding of their dynamics is essential in order to investigate the sensitivity of biological proxies to recent climate fluctuations in these locations. Despite the valuable contribution that has been made in examining recent temperature fluctuations and chironomid dynamics in extreme environments (Porinchu *et al*., 2010, 2009; Solovieva *et al*., 2005; Battarbee *et al*., 2002; Brooks *et al*., 2001; Clerk *et al*., 2000; Livingstone and Lotter, 1998; Lotter, 1997), muted temperature scenarios also need to be investigated. However, in less extreme environments human settlement is likely to be more extensive, and the human imprint on the landscape through time will often be greater. Human settlement can have a notable impact on lake ecosystems. In order to examine temperature change independently of human impacts, lakes should be selected where human impacts are minimal. The degree to which low impact human activities can confound a temperature signal is not adequately known. An understanding of chironomid response to human disturbances is essential in order to differentiate a temperature signal from a human impact response. In order to gauge the strength of chironomid response to changing temperature in areas with low-impact human activities, known climate records, along with known land-use records, can be compared with chironomid community change, as is done in this research.

2.4.3 Chironomids and Human Impacts on the Environment

Chironomids have been employed to investigate various human-induced impacts on the landscape; from pollution (Madden *et al*., 1992; Waterhouse and Farrell, 1985;

Winner *et al*., 1980) and atmospheric contamination (Birks *et al*., 2004; Ilyashuk and Ilyashuk, 2001) to vegetation changes (Langdon *et al*., 2010a; Brodersen and Lindegaard, 1999; Dvoraki and Bestz, 1982). A number of studies have investigated human impacts on lakes and their catchment (Langdon *et al*., 2010a; Zhang *et al*., 2006; Quinlan and Smol, 2002), and have made important contributions to the sensitivity of this fauna to various large-scale disturbances. Chironomids have been shown to react to human activities (Taylor *et al*., 2013; Heiri and Lotter, 2003) and several studies have shown that chironomids are responsive to changing lake productivity (Heinrichs *et al*., 2005; Hynynen *et al*., 2004; Meriläinen *et al*., 2003).

Surface water runoff and ground water seepage from a catchment into a lake system are natural ways in which organic pollutants can enter aquatic environments. These organic inputs can be important for lake ecosystems as small amounts are needed for species physiology. However, when these pollutants exceed the desired amount, ecosystem degradation can occur. It has also been shown that intensified human land-use has a detrimental effect on lake ecosystems, and in rural areas this has largely been a result of agriculture intensification, exhibited through eutrophication enhancement in the 20th century (Heinrichs *et al*., 2005). Societal eutrophication has been ranked as one of the most common water-quality problems in the world (Schindler, 2006). Human activities on land have accelerated the rate of nutrient enrichment of water bodies with the most notable nutrient loading has been from phosphorus and nitrogen. A number of studies have investigated the de-coupling of the chironomid-temperature relationship when historical and prehistorical human activities strongly affect the nutrient loading of lakes (Taylor *et al*., 2013; Gathorne-Hardy *et al*., 2009, 2007; Heiri and Lotter, 2005, 2003). While these studies demonstrate that human impacts can be discernible from a temperature signal in chironomid records, further work needs to be carried out on the sensitivity of chironomids to temperature change when lower impact human activities are overprinted on the landscape.

2.4.4 Complexity of Chironomid Research

Ecosystem vulnerability depends on species sensitivity to internal and external environmental changes. This vulnerability is further complicated by different controlling factors, internal feedbacks, and the influence of the catchment, in addition to the strength of these factors, which vary across geographical regions and through time. Human impacts on the landscape, climate change, and changes in within-lake variables, can all alter chironomid community composition. These effects are highly complex within aquatic systems, exposing more challenges for proxy indicators than to solely infer direct environmental information. It has recently been identified that there is a direct relationship between plant macrophytes and chironomids in shallow lakes (Langdon *et al*., 2010a), while total phosphorus has been shown to have an indirect effect as expressed through food-web dynamics (Langdon *et al*., 2006; Brooks *et al*., 2001). Furthermore, as human settlement patterns have a close relationship with forestry and agriculture (changes in arable and pastoral farming) through history, caution must be exerted when interpreting a chironomid stratigraphy in terms of temperature in an area that may have experienced vegetation change or nutrient input from human activities. Teasing apart these influencing mechanisms presents a difficult challenge in palaeolimnological research. To make matters more complicated, climate change is exacerbating eutrophication symptoms in lakes with a high nutrient concentration (Guo *et al*., 2013; Moss *et al*., 2011; Jeppesen *et al*., 2010). This is taking place through the direct effects of longer growing seasons and higher temperature gradients. However, effects are also indirect; for example, global warming is increasing the intensification of storm activity, which affects rainfall patterns and increases soil temperatures, in turn amplifying diffuse nutrient loading (Jeppesen *et al*., 2010). Rising temperatures and a longer growing season will increase nutrient loading by increasing the rate of mineralisation in catchment soils (Brookshire *et al*., 2011; Rustad *et al*., 2001). This scenario increases deoxygenation at the surface of lake sediments, subsequently releasing more nutrients into the lake water in summer (Jensen and Andersen, 1995). In lakes that have high nutrient concentrations, likely from agricultural input, temperature and eutrophication signals become complexly intertwined.

In chironomid research, this scenario is further complicated by the exact relationship between chironomid community composition and temperature (Eggermont and Heiri, 2012). Temperature affects organisms both directly (growth, reproduction, respiration and development) and indirectly through changes in other variables in the water body (water chemistry, oxygen concentrations, nutrient conditions). Additionally, in-lake variables independent of temperature and human impacts may cause a distortion in the chironomid temperature reconstruction (Eggermont and Heiri, 2012). An understanding of the relationship between chironomids, climate, in-lake dynamics and human impacts on the landscape is essential for isolating specific variables. In terms of climate, it has been widely suggested that chironomid-inferred temperatures should be examined in line with other proxy or instrumental evidence (Porinchu *et al*., 2007; Heiri and Lotter, 2005; Bedford *et al*., 2004; Klingbjer and Moberg, 2003; Battarbee 2000) in order to avoid errors in temperature interpretation from a chironomid assemblage. This study will tease apart human influences from the climate signal using a chironomid-based approach with available land-use and climate records through constrained and unconstrained ordinations. Therefore, the sensitivity of chironomids to human impacts on the catchment can be assessed together with the strength of the chironomid-temperature signal.

2.5 RESEARCH HYPOTHESES

The breadth of palaeolimnological studies using chironomids to reconstruct temperature in Europe have tended to focus on high-latitude or high-altitude locations, or over the late Glacial to early Holocene transition. Such studies have been invaluable in assessing the magnitude of climate change and the ability of chironomids to register such alterations. However, research needs to be carried out in locations that experience less extreme climate regimes, and over time periods which have lower magnitude climate shifts. This can provide a valuable insight into finer-scale climate fluctuations and events. The general aim of this study is to, firstly, assess the sensitivity of chironomids to less severe temperature change in Ireland using low and mid-elevation sites and, secondly, to reconstruct chironomid-inferred temperatures over the recent past (i.e. late 19^{th} to early 21^{st} centuries) and the Holocene. Palaeolimnological reconstructions and historical instrumental records have been used to address four key research questions in this thesis.

2.5.1 Long-term temperature trends at Markree Observatory are unique from existing (coastal) temperature records from the west of Ireland in that the record will exhibit characteristics of a more inland site due to geographic location and surrounding topography.

This study analysed long-term temperature patterns in the northwest of Ireland using a previously unexplored dataset from Markree Observatory, County Sligo. The Markree series extends back to 1842, making it one of the longest instrumental temperature records in Ireland. Despite its length, this record has been largely absent from past analyses of Ireland's long-term temperature trends, rendering spatial coverage for the extended Irish climate chronology incomplete. This research will be the first to provide an extended insight into the climate of northwest Ireland using a latent historical temperature record. It will compare the temperature reconstruction from Markree Observatory to the existing records in order to situate temperature trends in the County Sligo region within an island-wide context. It is hypothesised that the Markree temperature record will be unique to existing long-term records from the west of Ireland, which are from coastal locations (see Figure 4.4). Although the observatory is located only 7 km from the coast, the Markree record should exhibit characteristics of an inland site due to the mountains surrounding the northern and western areas of Sligo Bay, Markree's geographic location adjacent to the shallow Ballysadare estuary, and its location 'inland' from a southwesterly direction, which is likely providing a buffer from the moderating westerly/southwesterly wind regimes that dominate the Irish climate (Sweeney, 1997). Therefore, the Markree record should exhibit more temperature extremes and larger diurnal ranges compared to other 'coastal' sites.

2.5.2 Chironomid communities in western Ireland lakes are responsive to recent summer temperature change, including recent climate warming.

One valuable approach in understanding chironomid sensitivity to recent summer temperature change involves reconstructing quantitative temperature estimates using midge assemblages, and comparing them to instrumental temperature records across the same time interval (Guo *et al*., 2013; Larocque-Tobler *et al*., 2012; Self *et al*., 2011; Larocque *et al*., 2009; Porinchu *et al*., 2010; Cameron *et al*., 2002). This method allows the sensitivity of the relationship between chironomids and air temperature to be assessed in detail at decadal and sub-decadal timescales from recently deposited sediment. In this study, chironomid-inferred temperature estimates were reconstructed from three midge stratigraphies extracted from low to mid-elevation lakes. These were compared to a local instrumental temperature record (recorded at Markree Observatory) from 1875 to present in order to test the sensitivity of chironomids to climate change in the northwest of Ireland. Such an approach is unique in Irish research, provides important information on recent climate variability, and further assesses chironomid response to recent climate change.

2.5.3 The temperature signal and land-use changes can be identified and teased apart in the chironomid record.

Velle *et al*. (2010b) stressed that changes in nutrient concentrations and trophic state can mimic changes in chironomid assemblages in areas where temperature and lake productivity are correlated. However, when nutrient concentrations change as a result of human activities, unrelated to temperature, chironomid communities can register this signal. Thus, there is a problem with teasing apart chironomid response to land-use and temperature change. In order to gauge the strength of chironomid response to changing temperature in areas with low impact human activities, known climate records, along with known land-use records, were compared with chironomid community change over the recent past. An understanding of chironomid response to human disturbances is essential in order to differentiate a temperature signal from change due to direct human impacts. In Ireland, agriculture was a major part of the economy in the 19^{th} and 20^{th} centuries. Changes in agricultural practices have been abrupt over the last 150 years, with a major socio-economic shift in agricultural practices following the Great Irish Famine of 1845-1849 and an intensification in agriculture when the use of fertilisers increased ten-fold in the mid-20^{th} century (Douglas, 1992). This study will attempt to tease apart the temperature signal from direct human influences using chironomid assemblages from three lake sites. An investigation into the history of each lake catchment, combined with the climate of the region (using instrumental evidence), can allow an examination of the sensitivity of chironomid communities to these varying pressures. Constrained and unconstrained ordinations were used to explore the potential influences of temperature and land-use change on the chironomid communities through time. Therefore, the sensitivity of chironomids to low-impact practices, along with the assessment of the strength of the chironomid-temperature relationship, will be explored.

2.5.4 Chironomid communities in western Ireland are responsive to regional temperature fluctuations through the Holocene.

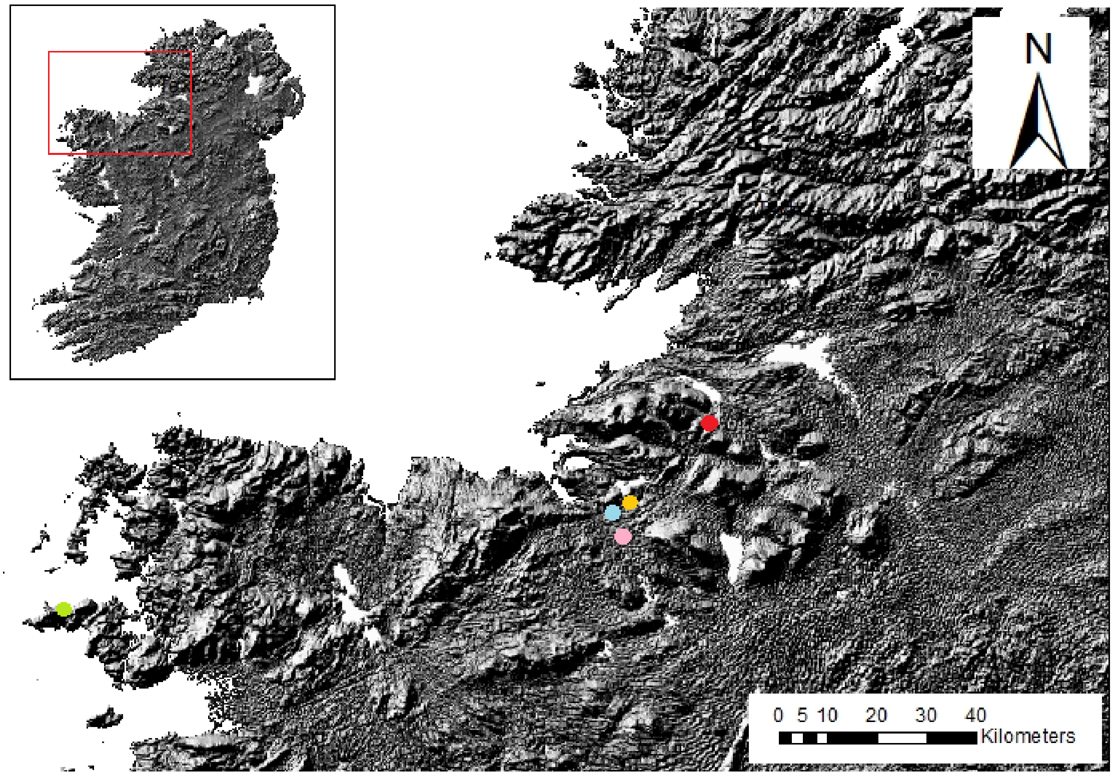
In Ireland, Holocene research has been mainly limited to pollen reconstructions (Edwards *et al*., 2007; Caseldine *et al*., 2007, 2005; Mitchell *et al*., 2006; Ghilardi and O'Connell, 2005; Molloy and O'Connell, 2004, 2002, 1995, 1992; Huang, 2002; Mitchell, 2002; O'Connell and Molloy, 2001; Jeličič and O'Connell, 2001; Edwards, 1985; Lynch 1981). While these studies have been invaluable, they have tended to focus on human impacts on the landscape. Temperature reconstructions over the Holocene have been largely neglected in Irish research. This research will use chironomids to reconstruct temperature over the Holocene in order to determine broad-scale climate fluctuations in an Irish context. Chironomid research is extremely limited in Ireland, and recent research has tended to focus on temperature change over the late Glacial to early Holocene transition (van Asch *et al*., 2012; Turner *et al*., 2010; Watson *et al*., 2010; Lutz, 2009) and historical human impact (Taylor *et al*., 2013; Ruiz *et al*., 2010). However, no work has been carried out over the entire Holocene using a chironomid-based approach to infer temperature in Ireland. As midges can track major and minor temperature fluctuations through time independently of precipitation (Eggermont and Heiri, 2012), they have the potential to capture the finer temperature fluctuations inherit in the Irish climate system. Furthermore, an understanding of Holocene temperature fluctuations can place modern temperature conditions in a broader context. This study will be the first to investigate temperature fluctuations throughout the Holocene using a chironomid-based approach.

CHAPTER 3: STUDY SITES AND METHODOLOGY

In order to investigate climate change and human impacts on lakes in western Ireland two main lines of enquiry were used: the exploration of temperature data from a previously unexplored climate record in Markree Observatory and chironomid-based palaeolimnological analysis. Chironomids were extracted from the centre of four different lakes. Three of these lakes were used to assess chironomid sensitivity to recent climate change and land-use histories. The fourth lake was used to investigate chironomid sensitivity to long-term Holocene climate fluctuations.

3.1 STUDY SITES

Study sites are located in the northwest of Ireland (Figure 3.1). Lough Meenagraun, Lough Lumman and Lough Ballygawley were selected due to their proximity to Markree Observatory, and by their varying degrees of isolation from human settlement over the last 150 years. Lough Nakeeroge is located in a secluded coastal location in northwest Ireland. The maritime climate at the site should be sensitive to North Atlantic phenomena through the Holocene, including regional fluctuations in freshwater inputs and any significant changes in thermohaline circulation (Caseldine *et al*., 2005; Turney *et al*., 2005).



Colour	Study site	Lat/Long	Elevation (m a.s.l.)
Pink	Markree Observatory	54° 10.51'N, 8° 27.45'W	35
Red	Lough Meenagraun	54° 22.94'N, 8° 12.98'W	379
Blue	Lough Ballygawley	54° 12.44'N, 8° 28.12'W	26
Yellow	Lough Lumman	54° 13.22'N, 8° 25.83'W	172
Green	Lough Nakeeroge	53° 59.53'N,10° 08.25'W	20

Figure 3.1 Study region in western and northwestern Ireland with all four study lakes and Markree Observatory.

3.1.1 Markree Observatory[1]

Markree Observatory is located 54° 10.51'N, 8° 27.45'W, approximately 1.5 km southeast of the town of Collooney in County Sligo and approximately 7.3 km southeast of the coastline. The station is positioned on slightly higher ground than the surrounding terrain (35 m above sea level) and 125 meters northwest of a meander of the River Unshin. Sparse vegetation dots the country landscape, yet no trees are located close to the observatory itself. Situated on a private estate, 200

[1] A detailed article on the Markree portion of this study can be found at McKeown *et al*., (2013).

meters to the side of a castle which has been recently renovated into a hotel, the grounds resemble those which existed in 1831 when the observatory was first established. Thus no microclimate effects from urban encroachment have been created over time.

3.1.2 Lough Meenagraun

Lough Meenagraun (54˚ 22.94’N, 8˚12.98’W) is the smallest of the four lakes (3 hectares) in this study (Figure 3.2). It is shallow with a maximum depth of 2.1 m and is considered a mid-elevation site (379 m a.s.l.). The lake is situated in the remote mountainous rural district of Glenade, Co. Leitrim. The landscape is comprised of pale orthoquartzitic sandstone (Geological Survey of Ireland, 2013), overlain with peat bog (Figure 3.3). Despite the remote location of the lake, pastoral farming exists in this area. Farm animals such as sheep and rams are present on the surrounding mountainous landscape. The lake is enclosed by a fence in order to keep the pastoral animals from mixing with other farm animals. Interestingly, this enclosure is not a modern fixture and has historic affiliations, identified from the National Monuments Service on Archaeology.ie (Figure 3.3). It must be noted that the farming in this area is at a diminutive scale and overall contemporary human settlement in the area is sparse.

The contemporary lake is classified as oligotrophic/mesotrophic. As the surrounding catchment comprises of bog, the lake water is acidic with a pH = 4.48. BOD is <1.75mg/l, conductivity is low at 20.43µS/cm and suspended solids is < 2mg/l (Table 3.1), implying that the modern lake is not presently experiencing a significant influx of material from terrestrial land disturbance. Few macrophytes were evident, and boulders and large rocks line the periphery and littoral zones of the lake. Vegetation surrounding this lake is dominated by *Sphagnum* and *Calluna vulgaris*, which are typical of Irish upland bog landscape.

Figure 3.2 Photograph of Lough Meenagruan taken on the day of sediment core extraction. This picture was taken from the southern section of the lake with the camera facing towards the north.

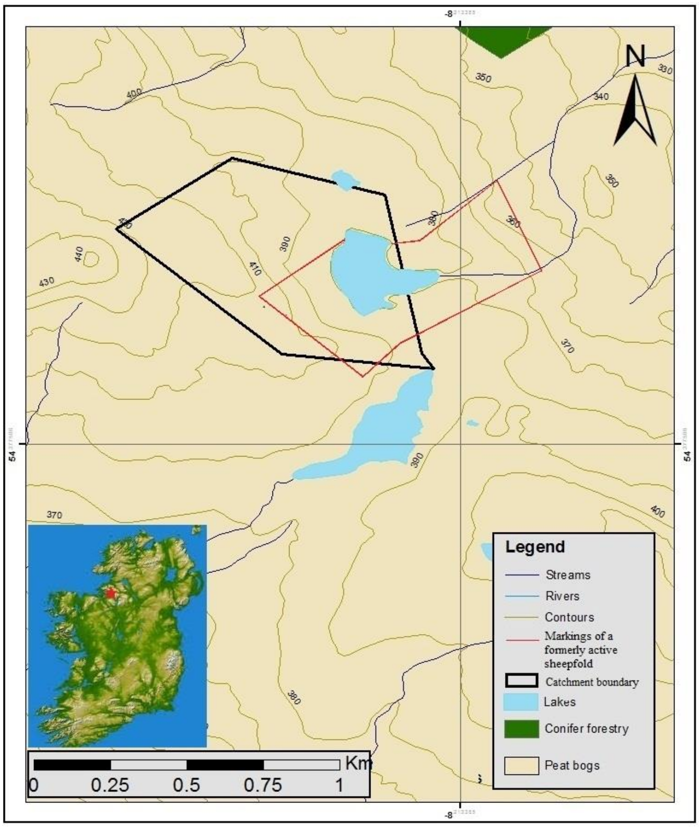


Figure 3.3 Contemporary land-use characteristics and watershed dimensions of Lough Meenagraun.

Table 3.1 Lake water chemistry analysis. BOD = Biological Oxygen Demand.

	Lough Meenagraun	Lough Lumman	Lough Ballygawley
BOD	< 1.75 mg/l	2.58 mg/l	< 1.75 mg/l
Ammonia	0.016 mg/l	< 0.015 mg/l	< 0.015 mg/l
Nitrate	< 0.2 mg/l	0.4 mg/l	< 0.2 mg/l
Nitrite	< 0.002 mg/l	<0.002 mg/l	0.004 mg/l
pH	4.48	4.68	7.81
Conductivity	20.43 µS/cm	28.1 µS/cm	115.8 µS/cm
Dissolved Oxygen	8.91 mg/l	8.98 mg/l	9.31 mg/l
Suspended Solids	< 2 mg/l	< 2 mg/l	3 mg/l
Total Phosphate	< 0.05 mg/l	< 0.05 mg/l	< 0.05 mg/l
Ortho Phosphate	< 0.05 mg/l	< 0.05 mg/l	< 0.05 mg/l

3.1.3 Lough Ballygawley

Lough Ballygawley (54˚ 12.44'N, 8˚ 28.12'W) is the largest of the lakes in this study (26.7 hectares) (Figure 3.4). It is shallow with a maximum depth of 1.1 m and is located at a low elevation (26 m a.s.l.). The lake is situated in a calcareous area which overlies gneiss bedrock (Geological Survey of Ireland, 2013), giving the lake water a pH of 7.81 (Table 3.1). The lake is situated 2.5 km northeast of Collooney town, County Sligo and located beside a regional class road (R284). Therefore, human impacts are a discernible feature at this site. Lough Ballygawley is situated within a forested area, Union Wood (Figure 3.5). This area is managed by Coillte and has been subjected to forestation since the 1960s, with intensified forestation since the 1980s along with phases of deforestation. Coillte is a commercial company which owns approximately one million acres of land across Ireland.

Figure 3.4 Contemporary photograph of Lough Ballygawley taken on the day of sediment core extraction. This picture was taken from the eastern section of the lake with the camera facing towards the west.

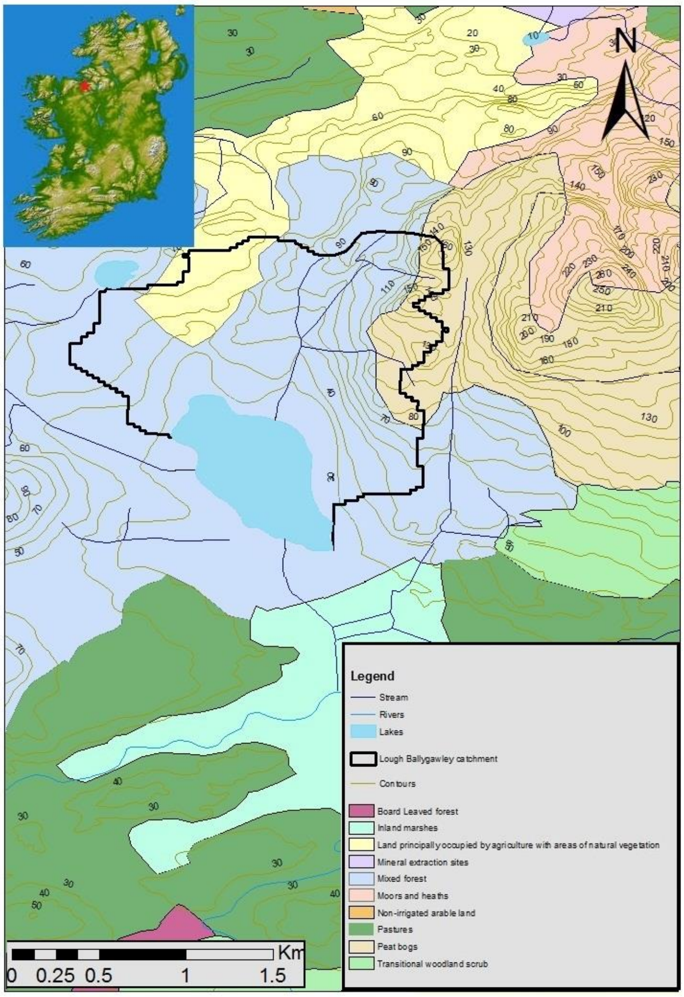


Figure 3.5 Contemporary land-use characteristics and watershed dimensions of Lough Ballygawley.

The primary terrestrial tree species that dominate the catchment are *Picea abies, Betula pendula, Fagus sylvatica* and *Abies procera.* Small numbers of *Quercus robur, Larix kaempferi* and *Pinus sylvestris* are also present. The lake is fringed by open reedswamp in which *Phragmites* and *Scirpus* play a part with some *Carex lasiocarpa, Carex rostrata* and *Equisetem fluviatile. Baldellia* and *Sparganium minimum* are also present at the site. Behind this, *Salix cinera, Betula pubescens* and *Alnus* grow on a peaty flat amongst *Molinia* and *Myria*. On a sandy substrate, the trees meet the lake water directly. In the woodland, *Scutellaria galericulata, Menta aquatic* and a small number of *Lycopus* grow. On the southern edge of the lake, *Carex paniculata* and *Osmunda* characterise the understory layer of the woodland which floods intermittently. Here, a great number of *Alnus incana* have been planted.

The lake is mesotrophic where suspended solids in the water were found to be 3mg/l and conductivity was 115.8µS/cm. Due to the location of the site in an area which is subjected to vegetation removal and human disturbance from the nearby road, this lake experiences the greatest level of contemporary human interaction with the catchment compared to all other lakes in this study.

3.1.4 Lough Lumman

Lough Lumman (54˚ 13.22'N, 8˚ 25.83'W) is a small (3.4 hectares), mid-elevation lake (172 m a.s.l.) (Figure 3.6). The lake is located in a secluded area on the eastern slope of Slieve Deaene and is located 2.6 km northeast of Lough Ballygawley. The lake overlies Granoblastic Kyanite and Pelite/semi-pelite paragneiss (Geological Survey of Ireland, 2013). A small outflow channel drains from the lake. The contemporary lake is acidic (pH = 4.68) due to the surrounding bog environment, and is oligiotrophic/mesotrophic. BOD is low 2.58mg/l, conductivity is low at 28.10µS/cm and suspended solids is <2mg/l (Table 3.1), which could signify that the contemporary lake is not presently experiencing any significant land disturbance from the surrounding catchment.

The lake is surrounded by peat bog, moors and heaths, and is located above a forested area that consists of traditional woodland scrub and coniferous forestry (Figure 3.7). Therefore, management of the woodland should have little to no impact on the lake. The main macrophytes present in the lake are *Horsetail Equisetum fluviatile, Carex rostrata, Nymphea alba* and small amounts of *Scirpus.* Along the lake edge there is *Molinia, Calluna, Pteridium* and *Rhododendron ponticum.* There is no evidence of human influence on the lake or its catchment in documentary sources. It is likely that the lake has not been subjected to significant human pressures.

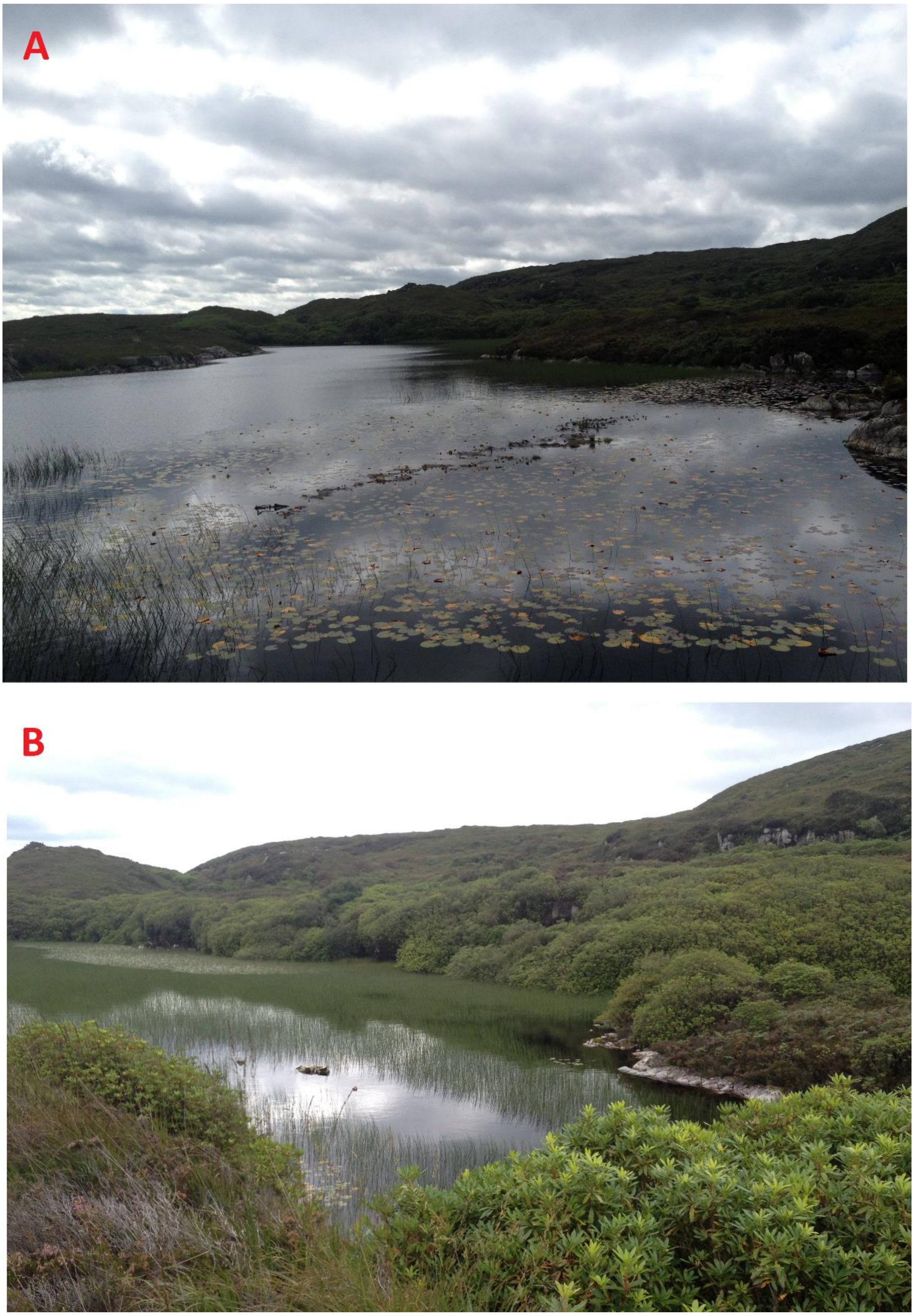


Figure 3.6 Contemporary photograph of Lough Lumman taken on the day of sediment core extraction. Photo A was taken from the northern section of the lake, while photo B was taken from the western shelf.

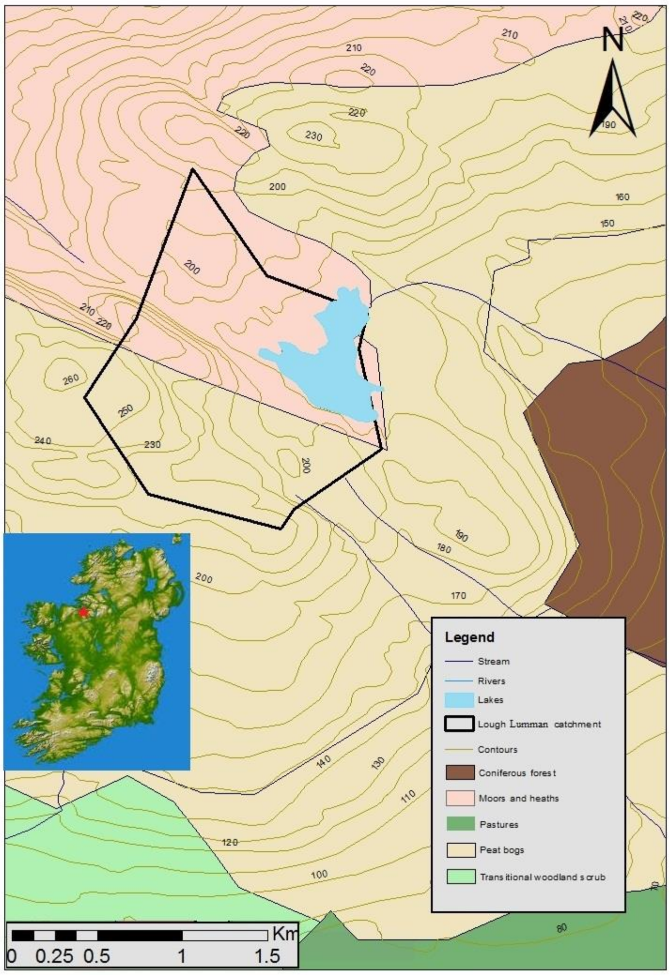


Figure 3.7 Contemporary land-use characteristics and watershed dimensions of Lough Lumman.

3.1.5 Lough Nakeeroge

Lough Nakeeroge (53˚ 59.53’N, 10˚ 08.25’W) is located on the northern coast of Achill Island, Co. Mayo in the west of Ireland. The lake is adjacent to the coast at 20 m a.s.l., with steep slopes to the south, east and west (Figure 3.8). Annagh Beach, located only meters to the north, gives Lough Nakeeroge a typical corrie shape (Figure 3.9). The lake is renowned for being the lowest corrie lake in Ireland. The lake is 0.65 km long and 0.2 km wide with a maximum depth of 4 m towards the centre of the lake. The catchment slopes consist of shallow peat soils on granite schist bedrock. *Molinia caerulea*, *Schoenus nigricans* and *Sphagnum* are dominant along the slopes and the lower plateaus around the lake. Only very small amounts of *Phragmites* line the periphery of the lake. Prehistoric features have been identified on the nearby headlands, despite the remote location of the lake. The land around the lake is not conducive to arable farming. It is likely that the land was used for grazing animals in prehistoric times. Achill Island's geographic position, on the eastern seaboard of the Atlantic Ocean, makes it an ideal location to investigate climate change during the Holocene due to its sensitivity to oceanic conditions and air masses affecting thermal characteristics of the nearby land.

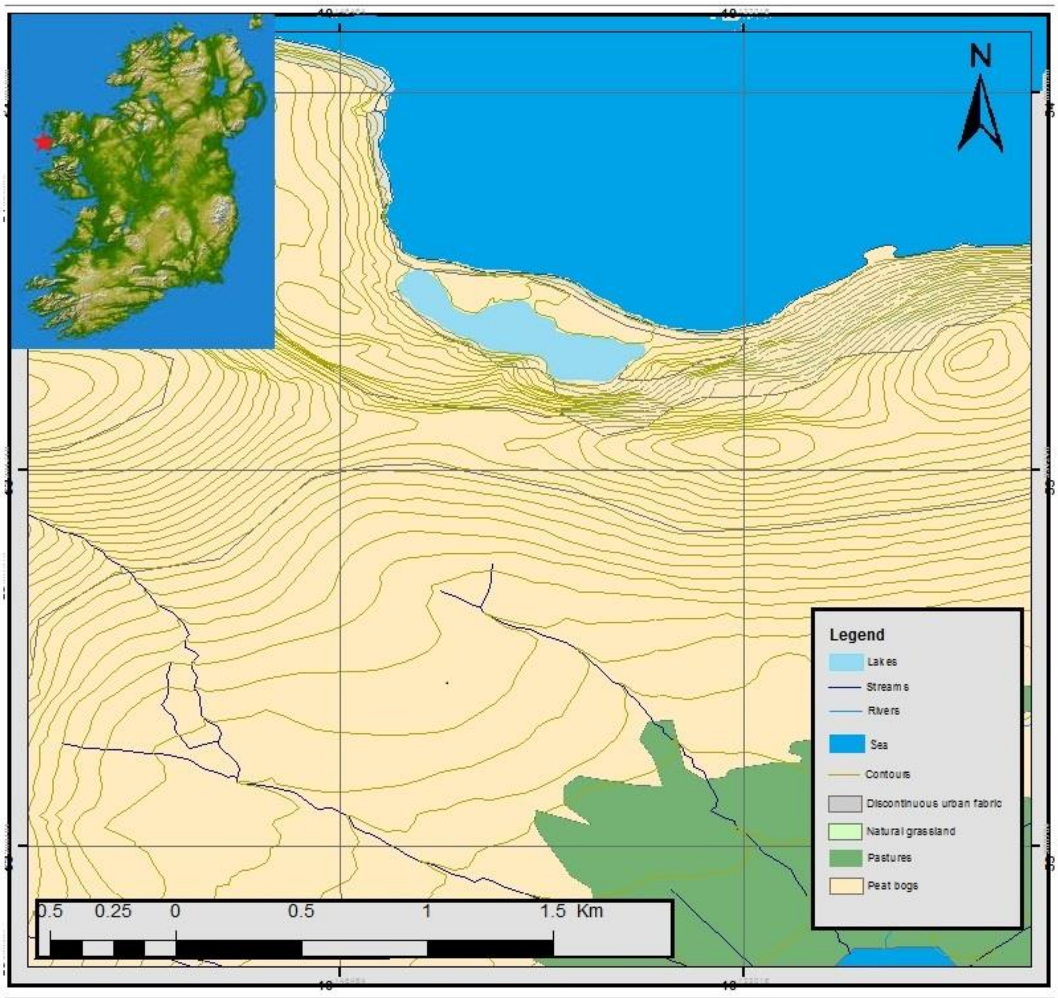


Figure 3.8 Contemporary land-use characteristics of Lough Nakeeroge.

Figure 3.9 Contemporary photograph of Lough Nakeeroge taken on the day of sediment core extraction. This picture was taken from a hill to the south of the lake with the camera facing towards the northwest.

3.2 MARKREE DATA

The principal instrumental data which is of concern in this thesis is the daily maximum, minimum and mean temperature values. The data were gathered from the original observers' logbooks and daily values were transferred from these documents to digital format. A typical page from a Markree logbook is shown in Figure 3.10. The date of data collection, the signature of the observer who recorded the meteorological information and handwritten notes referring to changes in instrumentation, time of observations and exposure are all highlighted in Figure 3.10. This information is vital for data correction and homogenisation.

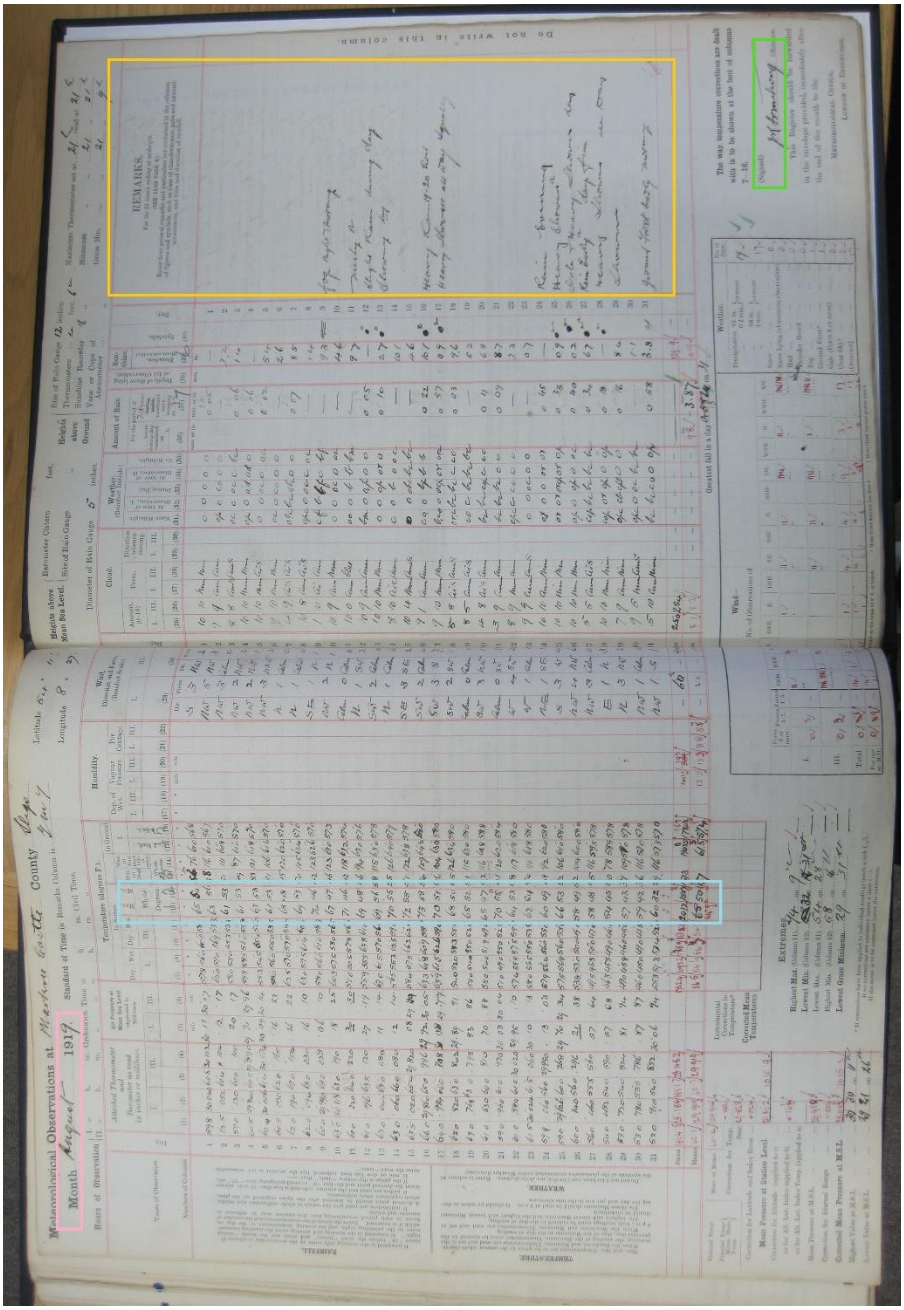


Figure 3.10 Typical page from the observers'handbook from Markree Observatory. Pink rectangle = date of recordings. Blue rectangle = daily maximum and minimum temperature recordings. Green rectangle = observers signature. Yellow rectangle = Handwritten comment referring to daily weather observations and changes relating to instrumentation and time of recording.

Markree Observatory began recording meteorological information in January 1842 using self-registering thermometers. Initial readings were taken in the morning from 1842 until 1862. From December 1863 until November 1874, recordings ceased when the founding observer, Edward Synge Cooper, passed away (Doberck, 1884). For 11 years the observatory lay inactive and it was not until a qualified Dutch astronomer, William Doberck, was employed at Markree by Edward Cooper's successor that meteorological data continued to be monitored and recorded again. Various qualified observers from Europe were appointed at Markree, which ensured the quality and consistency of the recorded information into the 20th century (Treanor, 2012; MacKeown, 2011). Maximum and minimum temperature values continued to be documented continuously until October 1998, when a break in the modern portion of the record unfortunately occurred as a result of the switch from manual to automated recording. Readings were not resumed until June 2008. Fortunately, as this gap is located in the modern recording era, maximum and minimum temperature data from Belmullet was available to supplement the Markree data (see Figure 4.1).

In order to explore the data comprehensively, the Markree temperature series was subdivided into three independent time series. Series I consists of the initial maximum and minimum temperature recordings from January 1842 to December 1863. This information was discovered within a paper published in the 19th century by one of the observers (Doberck, 1884). The original documents have never been discovered and it is thought that the observer, William Doberck, may have taken the original handwritten records with him when he moved to Hong Kong with his sister, Anna, in 1876. It was Anna Doberck who actually recorded the meteorological data at Markree, and has only recently received recognition for her keen interest in climatology (MacKeown, 2011). As Doberck was established at the Hong Kong Observatory when the 1884 paper was written, it is highly likely that the documents, should they continue to exist, are located there. Series I differs from Series II due to deviations in instrumentation and exposure. Caution must be taken when analysing Series I as the data are secondary, solely taken from a paper containing monthly mean maximum and minimum values. Series II is the longest series, comprising data from January 1875 to October 1998. This data was transferred from the original observer’s documents and stored in the National Met Éireann Library. Daily maximum and minimum values recorded in these original documents were calculated into mean maximum and mean minimum monthly values. Metadata relating to instrumentation and exposure have been extracted from the vast amount of additional handwritten remarks on the datasheets. Finally, Series III is the automated weather data which spans the period June 2008 to December 2011. This information was available in digital format from Met Éireann. No calibration was performed for the Series III data.

3.2.1 Data Calibration

Series I and Series II are of primary concern in this calibration. Instrumentation and exposure were investigated thoroughly and, where possible, corrections were applied. This required knowledge of specific thermometers and exposure of instruments throughout the record. Knowledge of such changes, and the specific time of any change, is essential in order to standardise the entire series accurately. Even though the instrumentation was monitored closely in Ireland by the Royal Irish Academy, a meticulous exploration of the handwritten weather documents was carried out in order to find remarks made by visiting inspectors. Such comments refer to, for example, changes of thermometer models, methods of recording and even exposure modifications. This information is crucial in order to comprehensively calibrate the data for both minor and substantial errors. Exposure is the most difficult category to calibrate for, as information regarding exact locations of thermometers is required, something that was often not noted in the observers' handbook and therefore lost. This is a frequent problem for the earliest data in many temperature reconstructions (Butler *et al*., 2005).

3.2.2 Series I

Instrumental calibration: Early thermometers were not as accurate as those used today, therefore knowledge of instrumentation is required for calibration purposes. Unfortunately the thermometer model is not known for this series. Doberck (1884) simply states that the thermometers were hung on the wall of the observatory. No evidence is available to determine the exact location of the thermometer, its height above ground, or whether it was on a north-facing wall. Evidence from this era suggests that two thermometers were universally in use in the first half of the 19th century for collecting maximum and minimum values - the Rutherford model and Six's model (Symons, 1897). The Rutherford model was usually hung on the wall of an observatory as the Six's model was too large. Therefore it is likely that the Rutherford model was the self-registering thermometer in use at this time. Unfortunately, as there is no overlapping time period with another independent thermometer or even spot readings registered over this series, a suitable correction cannot be performed. Therefore, no adjustments were made due to instrumentation in this series.

Time of reading: The advantage of maximum and minimum thermometers arises from their ability to be insensitive to the time of reading (Butler *et al.,* 2005). Originally readings were taken at 8 am until June 1846, then at 10 am until 1862. No correction was applied due to the negligible difference in observation times over such a short series.

Exposure: According to Doberck (1884) extreme air temperatures were not correctly registered in Markree over this period. Thermometers were hung on the wall of the observatory, but no information was provided relating to their exposure. Before the introduction of Stevenson Screens in the late 19th century, thermometers were usually placed on north facing walls. Thermometers placed in such locations, and thus shielded from direct solar influences, have been found to be in close agreement with Stevenson Screen readings (Butler *et al.,* 2005). However, no evidence is available to suggest that the thermometers in Series I were housed in a screen of any kind, and the instruments could have been exposed to direct sunlight. Unfortunately, the lack of metadata means that no calibration could be applied to this series to adjust for errors in exposure.

3.2.3 Series II

Instrumental calibration: Maximum and minimum self-registering thermometers were often broken easily due to the disturbance instruments were subjected to when resetting. Additionally, maximum thermometers were known to endure more occasional problems due to detachments of mercury from the main column (Butler *et al.,* 2005). Over time these minor errors could become more substantial, introducing systematic errors in the time series. Three maximum thermometers from Series II have been adjusted for such instrumental errors. From November 1874 until December 1883, a maximum thermometer of the Casella type 11395 was employed. Subsequent assessment of this thermometer by meteorologists in Markree found it to have an error of +0.5˚F. Thus 0.5˚F (0.28°C) was subtracted from the maximum data over this period. Negretti and Zambia model 55207 replaced the Casella maximum and this was found to have a lower-than-normal average reading. Again the data was adjusted by +0.8˚F (0.44°C) following suggestions outlined in the documents from 1884 to 1893. On 13th January 1894 this model was found to be broken and was substituted with the previous Casella 11395 until 1897. The previous correction of +0.5˚F was applied to the data over this interim period. The final maximum thermometer by Negretti and Zambia 94861 was in operation from 1898 to 1954. It is widely accepted that these thermometers leading into the 20th century are accurate to within 0.2˚F, therefore no correction was applied (Butler *et al.*, 2005). The thermometers used after 1954 have not been referred to in the documents. However it is known that a new maximum and minimum thermometer was purchased along with a new Stevenson Screen. This was likely part of the widescale national expansion of the Irish meteorological network. The correction applied to the data for this interim period will be discussed in the correction for exposure section.

For the minimum thermometer only one model appears to have been employed from 1874 onwards – Casella minimum model 10458. In the documents, one exclusive calibration is specifically referred to which states that this thermometer had an error of -0.5˚F from 1874-1883, therefore the readings were increased by 0.5˚F (0.28°C) to standardise the data. Despite the fact that this thermometer was used throughout the historical time series, no further errors were remarked, therefore no other corrections were applied.

Time of reading: Although it has been noted that maximum and minimum thermometers are generally insensitive to the time of reading (Butler *et al.,* 2005), considerable changes in observation times can have an effect on the data by introducing minor errors over long timescales. Originally, readings at Markree were taken in the morning, until March 1918 when thermometers were read at 9 pm. This was the practice until May 1963 when readings were reverted back to 9 am. According to Butler *et al.* (2005) this has a minor effect on the data. An empirically-determined amendment was applied to the record for the 12 hour effect using methods outlined in Coughlin (1998). The data was calibrated as follows: +0.08˚F (0.044°C) was applied to the monthly maximum readings and +0.19˚F (0.11°C) to the monthly minimum readings over the period March 1918 to May 1963 (Coughlin, 1998).

Exposure: Maximum and minimum thermometers were moved into a Stevenson Screen by 1875. Thus, for Series II, exposure changes were minor. In November 1954 a new Stevenson Screen was installed at the site. A historic photo of the observatory that includes a Stevenson Screen (photo taken in 1880, Figure 3.11) confirms that its modern location is only meters from its 19th century placement. The

Markree record states that the 19th century screen continued to be operated for one year, in line with the new screen in 1954-1955.

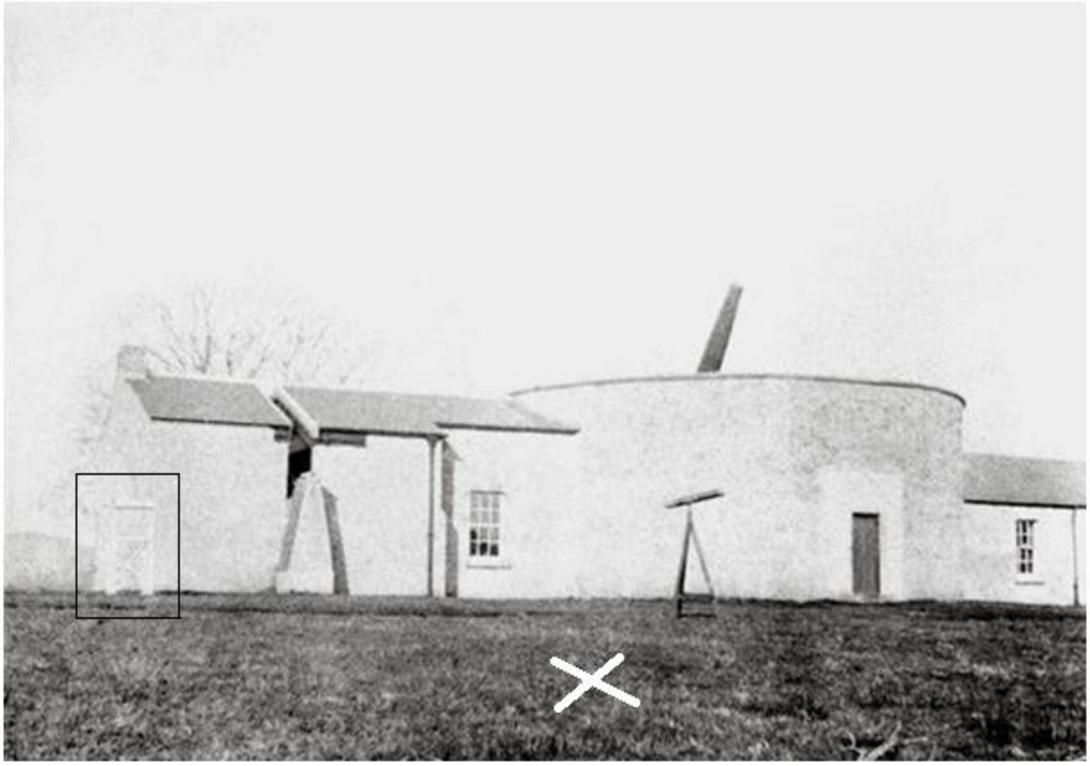


Figure 3.11 Photo of Markree Observatory taken in 1880. Stevenson Screen located outside the building on the left (within the rectangle). The location of the modern Stevenson Screen is indicated by the white x. Picture sourced from The Royal Astronomical Society, London UK.

This suggests that not only was the Stevenson Screen changed, but new instruments were installed in the new screen. Due to this overlapping period, a correction was easily calculated. A seasonal correction of -0.1°F (0.056°C) for winter, -0.07°F (0.039°C) for spring, -0.27°F (0.15°C) for summer and -0.1°F (0.056°C) for autumn was applied for Series II maximum values from 1874-1954. No correction was required for the minimum values.

3.2.4 The Belmullet patch

Recordings ceased for a short time in the modern portion of the time series, 1998-2007. Fortunately, as this gap is located in the modern recording era, maximum and minimum data from Belmullet (54°13'40''N, 10°0'25''W, 11 m a.s.l.) was used to supplement the missing Markree patch. The data from Belmullet was transformed to that of Markree using an overlapping period of 41 years from both stations. The adjustment was calculated using monthly maximum and minimum values from 1957- 1997. The mean difference between the two sites over this period was calculated for each month and used to patch the Markree series. A greater difference between the minimum values was noted, something that was unexpected as both sites lie in close proximity to the coast with only a 23 m difference in elevation. Table 3.2 reports the corrections applied for each month.

Table 3.2 Monthly corrections (˚C) applied to Belmullet data from 1998-2007 in order to reconstruct Markree patch

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	-1	-0.6	0.1	0.2	1	1.6	1.7	1.2	0.6	0	-0.8	-1.2
Min	-2.4	-2.3	-2.3	-2	-1.7	-1.5	-0.9	-1.5	-2	-2.2	-2.5	-2.4

3.2.5 Markree Series Analysis

In order to determine unique local temperature trends in the Markree dataset, a comparison was carried out between the Markree series and the five other long-term temperature records: Armagh, Birr, Malin Head, Phoenix Park and Valentia. All information was extracted from original observers' handbooks, stored in the Met Éireann library in Dublin city, and digitised for this analysis. Daily mean values for each month are available in digital format throughout the length of each record; however, the maximum and minimum data are only available post 1950 in this format. Therefore, monthly average maximum and minimum data pre-1950 needed to be manually transferred for this study. With the inclusion of Markree, the geographical spread of the six stations allows for a comparison of the various regional temperature regimes of Ireland, including the southwest (Valentia), north (Malin Head), west/northwest (Markree), midlands (Birr), northeastern midlands (Armagh) and east (Phoenix Park). Each record extends back into the 19th century, allowing comparison of long-term trends. In addition to a graphical comparison of trends, Pearson correlations were used to compare the Markree seasonal daily maximum, mean and minimum records with the other five datasets. Finally, as the NAO has been shown to exhibit a strong control on winter temperatures in Ireland (McElwain and Sweeney, 2010), winter temperatures from each station were correlated with winter NAO (Hurrell, 1995) to examine any geographical trends in the NAO-temperature relationship.

3.3 PALAEOLIMNOLOGICAL FIELD SAMPLING

3.3.1 Lake Coring Strategy

Duplicate sediment cores from Lough Meenagraun, Lough Ballygawley and Lough Lumman were extracted near the centre of each of the three lakes in the autumn of 2009, using a Glew mini-corer (Glew, 1991) which was deployed from an inflatable raft. The second core was taken to ensure there was enough material available for this study. Core lengths were 27 cm and 26 cm for Lough Meenagraun. Lough Ballygawley sediment cores were shorter, at 23.5 cm and 21.5 cm. The longest sediment cores of these three lakes were extracted from Lough Lumman, with lengths of 41.5 cm and 39 cm. The longer cores were used for all analysis and it was assumed that all cores covered the span of the Markree Observatory instrumental record. Sediment core characteristics will be discussed in each results chapter.

Each of the cores were sectioned at the lake side at 0.5 cm intervals, placed in clearly labelled whirl-pack® bags and transported to a refrigerator in a laboratory at the National University of Ireland Galway. All sediment analysis was limited to one core from each site in order to avoid errors arising from differing sedimentation rates. During sediment extraction, measurement of surface water temperature, dissolved oxygen concentration and Secchi depth were taken (Table 3.3).

Table 3.3 Measurements taken on day of core extraction. DOC = Dissolved Organic Content.

	Lough Meenagraun	Lough Lumman	Lough Ballygawley
Secchi depth	1.0 m	0.2 m	0.5 m
Surface water temperature	16˚C	16.1˚C	19.2˚C
Bottom water temperature	16˚C	16.1˚C	19.1˚C
DOC water surface	14.2 ppm	9.9 ppm	12.3 ppm
DOC water bottom	11.9 ppm	8.9 ppm	10.3 ppm

In July 2010, water samples were collected 0.5m below the water surface from each lake, placed in pre-cleaned polyethylene bottles and sent overnight to Eurofins in Dundalk for chemical analysis. Each sample was tested for levels of ammonia, nitrate, nitrite, conductivity, suspended solids, total phosphates, biological oxygen demand (BOD) and pH (Table 3.1).

Two overlapping cores, core A and core B, were extracted in 1 m segments near the centre of the Lough Nakeeroge basin using a Livingstone corer (Wright *et al*., 1984). This was carried out in June 2009[2]. The cores were labelled and wrapped in plastic film and aluminium foil before being transported to a laboratory in the University of Exeter, UK. The top 50 cm of most recent sediment was not collected as this sediment was too watery and coring equipment for keeping this sediment intact was not available on the day of coring. Therefore, the core begins at 50 cm below the sediment surface until it reaches a depth of 362 cm. Sediment cores composing core A were taken between depths of 50-142 cm, 150-243 cm and 280-349 cm. Gaps in the core A sediment sequence exist between 143-149 cm, and again, between 244-279 cm. Core B is composed of sediment cores taken a depth sequences of 100-196 cm, 200-299 cm and 300-362 cm. One short gap in this sequence exists between a depth of 197-199 cm. A 3.12 m contiguous master core was created from the two overlapping cores based on correlation of loss-on-ignition (LOI) at 550˚C, overlap of important chironomid taxa and radiocarbon dating (see section Figure 8.2 and 8.3, Chapter 8). The sediment cores were sub-sectioned at 1 cm intervals and stored in the Geography Department’s laboratory at the University of Exeter.

3.3.2 Lake Bathymetry

Bathymetric maps were created for Lough Meenagraun, Lough Lumman and Lough Ballygawley. The morphology of lake basins can affect physical, chemical and biological variables within lakes (Jura *et al*., 2012). Therefore, the shape of a lake basin can reveal important information linking physical structure to biological activity. The morphology is best illustrated using a bathymetric map, where depth contours are constructed using sonar technology. Recent development in equipment has increased the portability and precision of imaging underwater environments. Prior to this study, no detailed bathymetric maps were available for the lakes under investigation.

[2] This core was extracted by Dr. Gareth Thompson and his team from the Geography Department, University of Exeter, England.

The Humminbird version 788 ci HD system was used in conjunction with Dr. Depth version 4.0.10 mapping software to take real time depth measurements of the lake basin. The dual beam down-imaging and side-imaging methods employed in this study are well suited for the morphologic investigation of shallow water lakes. The transducer produced a 200 kHz narrow conical beam which allowed increased vertical and horizontal resolution (Sonnenburg and Boyce, 2008). Depth transects were developed using an Intex® inflatable raft driven manually or with a Fladen® 12v electric motor. The raft was guided across the water to develop a series of interconnecting depth transects until an interpolated map (with a 0.5 m interpolation-limit) was fully constructed.

3.3.3 Data Loggers

Chironomid larvae can show a direct physiological response to summer air temperature. When and how the lakes warm up depends on their location, altitude, bathymetry and depth (Brodersen and Anderson, 2000). Air and water temperature was assessed at the Lough Meenagraun, Lough Lumman and Lough Ballygawley sites in order to determine the relationship between air and water temperature at each lake site and also the between lake study sites and Markree Observatory. Air temperature was used to determine local temperature trends and how they compare to the Markree temperature record. Daily mean water and air information from the data loggers, for the three lake sites, were compared to the Markree daily records, between April 2010 and September 2010, to get a detailed insight into daily temperature differences over these warmer months between each site. Hourly water and air temperature data was measured using Onset Hoboware® temperature data loggers. These devices were placed at each site between one and three years, depending on the reliability of instrumentation and site visitation. Data loggers for measuring air temperatures were positioned 1.2 m above ground level and in the shade, when possible, along the periphery of each lake. A second data logger was suspended from a float 0.5 m below the water surface at the centre of each lake. After one year, the devices were collected and the data was downloaded for analysis. Data loggers were again launched for a second year. Table 3.4 displays the length of recording time for each data logger at each site. For Lough Lumman the data logger placed in the water stopped working in the first few days. However, data was collected for the following year when this faulty data logger was replaced with a functioning one. Furthermore, the data logger for measuring water temperature at Lough Meenagraun was removed from the site during the first year of measurement. Another data logger was placed at a neighbouring lake, Lough Nabrack, and this data logger was also cut from the float at this lake. Therefore, no water temperature data are available for this site. Despite the problems encountered with the water data loggers at both sites, air temperature was recorded continuously. For Lough Ballygawley, air temperature was recorded for a two year period while water temperature was collected over a three year period.

Table 3.4 Length of data logger recordings

	Lough Meenagraun	Lough Lumman	Lough Ballygawley
Air temperature	21st Sept 2009 - 11th Aug 2011	21st Sept 2009 - 11th Aug 2011	21st Sept 2009 - 11th Aug 2011
Water temperature	X	4th Aug 2010 - 11th Aug 2011	21st Sept 2009 - 28th Oct 2012

3.4 DATING

To develop chronological controls radioisotopic ages were obtained along the sediment cores using ^{210}Pb and ^{14}C dating techniques. Due to its relatively short half-life of 22.3 years, ^{210}Pb can reliably date sediments to 150 years before present (Appleby, 2013). As this time span corresponds well with the length of the instrumental record, this dating method is ideal for the short cores in order to establish each sediment chronology. Thirteen bulk sediment samples from Lough Meenagraun, 13 from Lough Lumman and 12 from Lough Ballygawley were analysed for ^{210}Pb content (Table 3.5).

Table 3.5 Samples taken for ^{210}Pb analysis

Lough Meenagraun Depth Range (cm)	Lough Lumman Depth (cm)	Lough Ballygawley Depth (cm)
0 - 0.5	0 - 0.5	0 - 0.5
0.5 - 1	0.5 - 1	0.5 - 1
1 -1.5	1 -1.5	1 - 2
2 - 2.5	2 - 3	2 - 2.5
3 - 3.5	3.5 - 4.5	3 - 3.5
5 - 5.5	5.5 - 6.5	5 - 5.5
7 - 7.5	8.5 - 9	7 - 7.5
8.5 - 9	10 - 10.5	9 - 9.5
10 - 10.5	12.5 - 13.5	12 - 12.5
14 - 14.5	17.5 - 18.5	15 - 15.5
18 - 18.5	23.5 - 24.5	18.5 - 19
22 - 22.5	30.5 - 31.5	22.5 - 23
26.5 - 27	40.5 - 41	

A 0.5 cm sampling interval was used to constrain the chronologies. However, in some cases a 1 cm sampling interval was used as the minimum amount of sediment required to carry out the ^{210}Pb analysis was insufficient at certain depths. Samples were chosen using an exponential depth sequence, with the top of the core containing more samples (Appleby, 2013). ^{210}Pb analysis was carried out by MyCore Scientific, Inc., Deep River, Ontario, Canada. Prior to sending sediment for ^{210}Pb analysis, the 37 samples were dried and weighed, and percent moisture and percent organic matter were calculated for each depth and intermediate depth to identify any inconsistencies in lake sedimentation through time. Samples were dried and ground using a miniature mortar and pestle and placed in a 50 ml plastic sampling vial before being sent away for ^{210}Pb analysis. ^{210}Pb ages were calculated using the dry mass accumulation rate (DMAR) (Appleby, 2013). Age-depth models were constructed using SigmaPlot version 10.

Two AMS radiocarbon dates of humic acid fraction of bulk sediment were obtained for each of the three lakes, Lough Meenagraun, Lough Lumman and Lough Ballygawley. All dates from these lakes were taken from core A. All analysis was performed on the humic acid fraction of bulk sediment due to the lack of macrofossils in each sediment core. In Lough Ballygawley a sample was taken from the top of the core and one from the bottom in order to correct for a potential reservoir effect due to the presence of carbonate rock in the area (Table 3.6). In Lough Meenagraun and Lough Lumman a sample for ^{14}C dating was taken from the bottom of the core and another sample was taken just below the ^{210}Pb dated section of each core (Table 3.6). ^{14}C dates were calibrated using Clam version 2.1 (Blaauw, 2010) and R version 2.15.2. Calendar age point estimates for depths were based on weighted average of all age-depth curves based on the age-depth models themselves. Radiocarbon dates for Lough Meenagraun, Lough Lumman and Lough Ballygawley were found to be unreliable. The samples taken from the middle section of the cores of Lough Meenagraun and Lough Lumman were found to be either as old as or older than the bottom sample. As all of the lakes are either bordered by bog or have input streams draining bog areas it is likely that ^{14}C-depleted bog material is entering the lake from its surroundings, thus, contaminating in-lake sediment layers by the reworking of older material through newer sediments. This is essentially distorting the levels of ^{14}C, which is a common problem in bog lakes in western Ireland (Shore *et al*., 1995).

Table 3.6 Radiocarbon Ages. Discarded date is displayed with a strikethrough.

Lake	Depth (cm)	Material	^{14}C Date (yr BP)	AMS $\delta^{13}C$ (Cal yr BP)	Calibrated Age (Cal yr)	Relative area under distribution
Lough Meenagraun	12.5 - 13	Humic Fraction of Bulk Sediment	1,642 +/- 23	-31.5	1,561 BP	0.903
	26.5 - 27	Humic Fraction of Bulk Sediment	1,619 +/- 32	-23.7	1,490 BP	0.987
Lough Lumman	19 - 19.5	Humic Fraction of Bulk Sediment	1,664 +/- 21	-31.5	1,570 BP	0.988
	40.5 - 41	Humic Fraction of Bulk Sediment	1,560 +/- 49	-27.2	1,446 BP	1.000
Lough Ballygawley	surface	Humic Fraction of Bulk Sediment	862+/-25	-30.3	761 BP	0.881
	22 - 22.5	Humic Fraction of Bulk Sediment	2,151+/-38	-27.0	2,111 - 2,267 BP	0.620 - 0.322
Lough Nakeeroge	76 - 77	Bulk Sediment	2,068+/-37	-25.9	2,029 BP	0.999
	~~168 - 169~~	~~Bulk Sediment~~	~~4,349+/-35~~	~~-23.5~~	~~4,911 BP~~	~~0.947~~
	180 - 181	Bulk Sediment	3,874+/-38	-27.4	4,325 BP	0.915
	224 - 225	Bulk Sediment	4,835+/-36	-30.0	5,592-5,608 BP	0.527 - 0.423
	288 - 289	Bulk Sediment	6,586+/-40	-26.8	7,474 BP	0.810
	389 - 390	Bulk Sediment	8,993+/-45	-23.2	10,182 BP	0.777

Age-depth models for the Lough Nakeeroge core were based on AMS ^{14}C ages of bulk sediment. The problems encountered with ^{14}C dating sediment layers in the other three lakes were not experienced in this lake. Six AMS radiocarbon dates were obtained along the sediment master core. Three dates were taken from core A and three dates from core B. All ages for this lake were calibrated using Clam version 2.1 (Blaauw, 2010) and R version 2.15.2. Dates for this lake are reported throughout the thesis in calibrated years before present (cal. yr BP). The midpoint of the 2-sigma range with the highest probability of occurrence was used to create the cal. yr BP ages employed in the age-depth model. The bulk sediment date at 168-169 cm was discarded, along with the entire meter-long section of the core from which the sample was taken (see core re-alignment section in Chapter 8), as the date as this depth was too old and did not follow with the other dates. The discrepancy is likely due to problems with recorded depth taken on day of core extraction.

3.5 LABORATORY ANALYSIS

3.5.1 Loss-on-ignition (LOI)

Loss-on-ignition (LOI) analysis (Heiri *et al*., 2001) was carried out to establish percent organic and inorganic carbon content throughout each of the cores from all four sites. Analysis was carried out at 0.5 cm intervals at Lough Meenagraun, Lough Lumman and Lough Ballygawley. For Lough Nakeeroge samples were evaluated at 1 cm intervals. From each of the sample layers, 1 ml of sediment was dried at 100˚C for at least 24 hours. The dry samples were subsequently weighed and heated in a muffle furnace for four hours at 550˚C to burn off the organic content. Samples were then weighed in order to determine the amount of organic content lost. Organic carbon content was calculated then as the difference in weight between the sediment dried at 100ºC and the ash created following ignition at 550ºC within a high temperature muffle furnace:

% Organic Matter = [Weight of 550 ºC Ash] / [Weight Post 100 ºC Dry Sample] x [100]

Each of the samples was heated once more at 950˚C for two hours. When samples cooled, they were weighed to determine carbonate loss. Inorganic carbon was calculated as the difference in weight between the sediment heated at 550˚C and the ash created at 950ºC within a high temperature muffle furnace:

% Inorganic Carbon = [Weight of 950ºC Ash] / [Weight of 550˚C] x [100]

The final LOI (%) values indicate the proportion of total dry weight that was lost due to ignition at each temperature.

3.5.2 Chironomid Extraction

Chironomid analysis was undertaken at the National University of Ireland Galway, following standard procedures outlined by Walker (2001). In order to prepare the samples for midge recovery, between 0.5 ml and 5 ml of sediment was deflocculated in 10% KOH solution before being heated at 30˚C for 30 minutes. The sample was then sieved through a 90 µm mesh. The remaining material was subsequently rinsed with distilled water before being expelled into a beaker. The resulting material was transferred into a Bogorov plankton counting tray where chironomid head capsules were handpicked using a Motic® SMZ series dissection scope at 10-40x magnification. Chironomids were placed on cover slips and permanently mounted on slides with Entellan® solution for identification using a Motic® B3 Professional series compound microscope at 100-400x magnification. Taxa were identified to genus, sub-genus and species level based on Wiederholm (1983), Rieradevall and Brooks (2001) and Brook *et al*. (2007). Chironomid fossils of less than half a head were discarded and those that possessed half a head (counted as half a head) or greater (counted as a full head) were recorded appropriately.

Chironomids were handpicked at various sampling resolutions: approximately 4 cm intervals over the Lough Nakeeroge sediment core, 0.5 cm intervals from the other three lakes over the ^{210}Pb dated portion of each record and then at 1cm intervals below this zone. At each depth range the least amount of sediment was used to extract the desired amount of 50 head capsules. The average number of head capsules enumerated per sample was 77 from Lough Meenagraun, 76 from Lough Lumman, 69 from Lough Ballygawley, and finally 71 from Lough Nakeeroge. At each sampling depth, the amount of sediment required to attain the minimum number of head capsules varied from 0.5 cm^3 to 5 cm^3. Due to low abundance of midge remains at certain sample depths from the Lough Ballygawley core, the minimum requirement of 50 head capsules could not be recovered from five samples. In these samples, 40 to 49.5 head capsules were extracted, and although this is not desirable, it is still statistically viable (Larocque *et al*., 2001).

3.6 STATISTICAL ANALYSIS

3.6.1 Chironomid Data

A chironomid stratigraphy was created for each lake site using the programme C2 version 1.4, developed by Steve Juggins, Newcastle University UK. Relative abundances were used instead of absolute abundances in order to eliminate potential bias caused by changes in sedimentation rates and sediment forcing (Birks and Gordon, 1985). Stratigraphic changes in the composition of each chironomid assemblage were assessed by optimal sum-of-squares partitioning (Juggins, 1991), based on taxa percentages. Statistically significant zones identified using the broken stick model (BSTICK) designed by Bennett (1996). This model was used to test the significance in the reduction of variance of each additional zone with the reduction of variance as predicted by an unstructured stratigraphy. In order to interpret the compositional structure and species turnover of each chironomid community, all ordinations were produced using square-root transformed chironomid percentage data for all common taxa. Common taxa from each lake were identified as those present in at least two samples with a relative abundance of 2% in at least one sample. Principal Component Analysis (PCA) and Detrended Correspondence Analysis (DCA) were applied through each midge stratigraphy. In all cases, PCA showed the strongest performance. For Lough Meenagraun, Lough Lumman and Lough Ballygawley analysis was divided into two lines of enquiry: the ^{210}Pb-dated portion of each record was statistically evaluated independently of the rest of the core, followed by analysis of the entire stratigraphy. The rationale for this dissected investigation lies in the need for reliably dated material (^{210}Pb section) for a comparison with meteorological and historical land-use records. The analysis of the entire core for each of these three sites allowed an extended insight into the climate of these regions beyond the instrumental record, despite the absence of reliable dates.

To provide a deeper exploration of the relationship between chironomid community change and climate variables in the ^{210}Pb-dated sections of Lough Meenagraun, Lough Lumman and Lough Ballygawley, redundancy analysis (RDA) was performed. RDA is a constrained linear ordination technique to determine the variation within the chironomid community constrained to the chosen environmental variables. As the Markree temperature and precipitation data extend back to 1880, all RDA's were carried out from 1880 to 2009. Partial RDAs were then used to examine the importance of each variable over-and-above the explanatory power of the other remaining variables. Canonical coefficients, T-tests and eigenvalue ratios ($\lambda 1/\lambda 2$) for each of the selected variables were used to determine the primary environmental controls for each of the chironomid profiles in the three lakes. All ordinations were performed using CANOCO version 4.54.

3.6.2 Chironomid-Temperature Transfer Function

Chironomid-inferred temperatures were reconstructions from each chironomid community in the four study lakes. The inference models were generated using the 50-lake training set from western Ireland (Potito *et al*., forthcoming). The training set identified summer air temperature as the most influential control on modern chironomid distribution in western Ireland (Potito *et al*., forthcoming). This study was the first to create a chironomid-based summer air temperature inference model using this training set, as previous chironomid research in Ireland and the UK has employed the Norwegian training set to develop transfer functions. Based on a one-component weighted-average (WA) classic model of lake characteristics, chironomid assemblages were deemed an excellent predictor of summer air temperature in west of Ireland region ($r^2_{jack} = 0.60$), root mean squared error of prediction (RMSEP) = 0.51, and a maximum bias of 0.64.

To assess the sensitivity of chironomid community to recent climate and environmental change, all environmental and climate records were adjusted to match the resolution of the lake data. Each 0.5 cm to 1 cm section of the lake sediment represented an average of climate and environmental data over that interval. This allowed for a detailed comparison between the chironomid, climate and environmental data.

3.7 HISTORICAL LAND-USE DATA

In order to gauge the sensitivity of chironomids to temperature change in areas where humans have been active, known historical records of land-use change in each lake catchment were needed. Lough Meenagraun and Lough Ballygawley have a history of low- to mid-impact human activity, while Lough Lumman did not have any such history in the lake or its catchment. Newspaper articles and other secondary evidence containing historical information relating to local agricultural activities, which were stored in local libraries, were explored. This was done in an effort to identify human activities in these remote rural areas in the northwest of Ireland. While contemporary land-use information was readily available, information relating to the history of each site before the mid-20th century is limited. As a result, it was necessary to utilise every possible resource to its full extent.

An exploration of historical human activity around each lake was carried out using the interactive GIS database compiled by the Archaeological Survey of Ireland (ASI). The database contains all known monuments and remnants of former human activities for the entire island and was therefore useful in investigating these remote study sites. In addition, local census data was examined to determine whether or not significant population change occurred at each study site. This information is available from the Central Statistics Office at Electoral District (ED) level (Kelly and Fotheringham, 2011), which is the smallest legally-defined administrative area in the island. The record dates to the mid-19th century. Here, the goal was to use analysis of population change at the ED level to complement evidence of local land-use change, in turn helping to define the extent of human activities in each lake catchment before the mid-20th century.

Fieldwork surveys carried out by Coillte, from the 1980s to present, were examined to determine the extent of forestation and deforestation over the recent past. The records contained information relating to tree species, where and when they were planted, and the year in which they were felled/thinned. These records contain information dating to 1900. Modern orthophotography maps from 2000 and 2005, as well as Ordinance Survey Ireland's hand-drawn maps dating to the 19th century, were examined in order to visually explore landscape modifications around the lakes.

CHAPTER 4: MARKREE OBSERVATORY

4.1 MARKREE ANNUAL TEMPERATURE MASTER SERIES

Annual averages for daily maximum, minimum and mean temperatures from Series I, Series II and Series III along with the Bellmullet patch are presented in Figure 4.1. Series I appears to be inconsistent with the other series as maximum and minimum values appear far too extreme. The reason for such a disparity lies in the unreliability of early instrumentation and lack of knowledge regarding the effects of exposure. A greater understanding of observation procedures, instrumentation and exposure during this series may allow the data to be standardised. However this would require the discovery of further metadata for Markree covering this initial recording period. To date, such information is unavailable and consequently no calibrations were performed for Series I, meaning the data remains in its original raw format. Although Series I could not be calibrated as part of a longer chronology, relative temperature changes such as the colder conditions of the mid-1850s, which coincide with a solar minimum in December 1855 (Hickey, 2012), can be observed. The gap between Series I and Series II marks a period of inactivity in the observatory from December 1863 until November 1874. Throughout Series II data was recorded almost continuously with only minor breaks in recording occurring from September to November 1898 and May to November 1969. This series has been comprehensively calibrated, and is therefore comparable to modern data. The converted Belmullet data filling the Markree gap has sufficiently connected Series II and Series III, allowing a near-continuous series from 1875 to present.

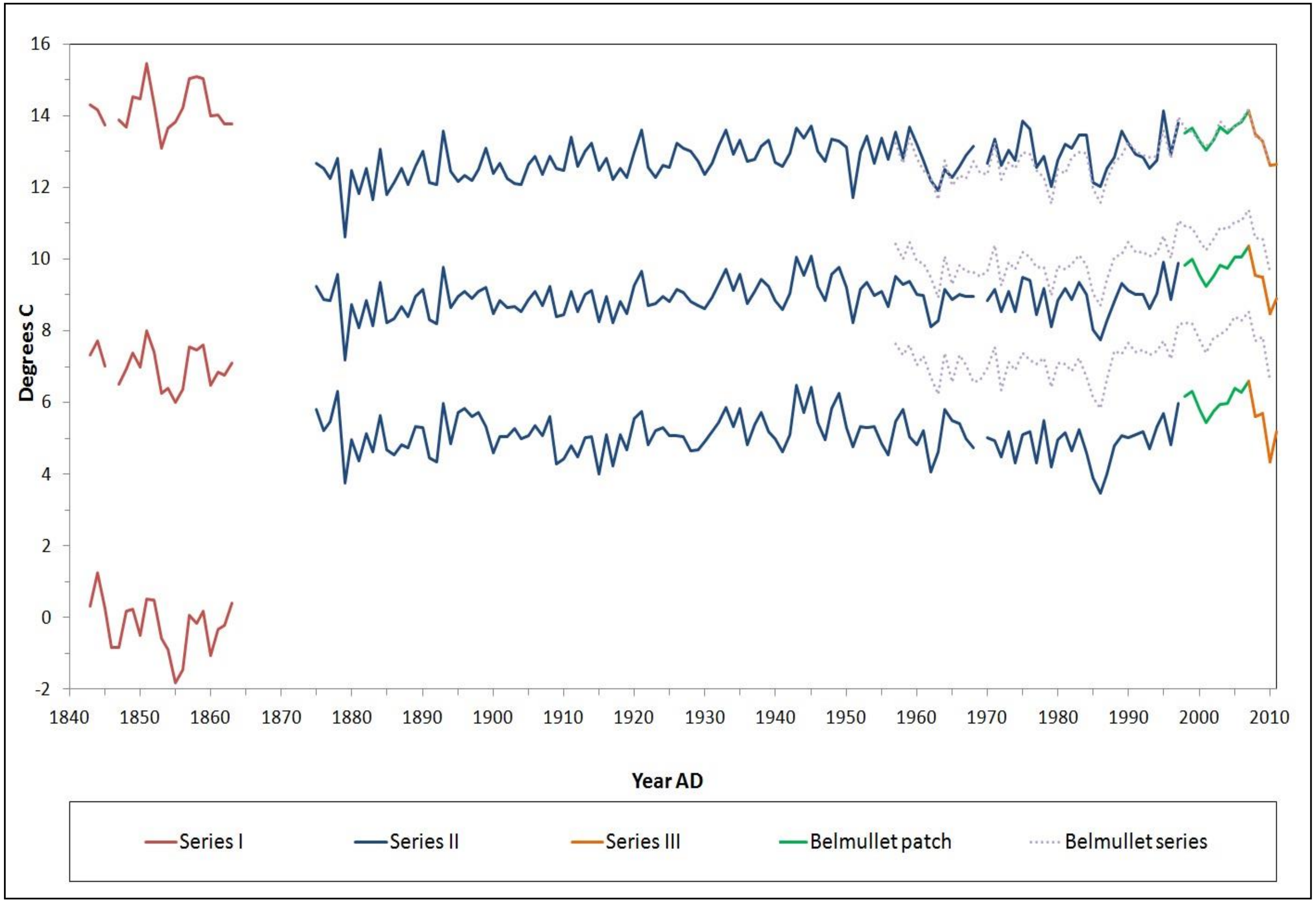


Figure 4.1 Fully corrected annual time series for average daily maximum, mean and minimum temperatures from Markree Observatory, 1842-2011.

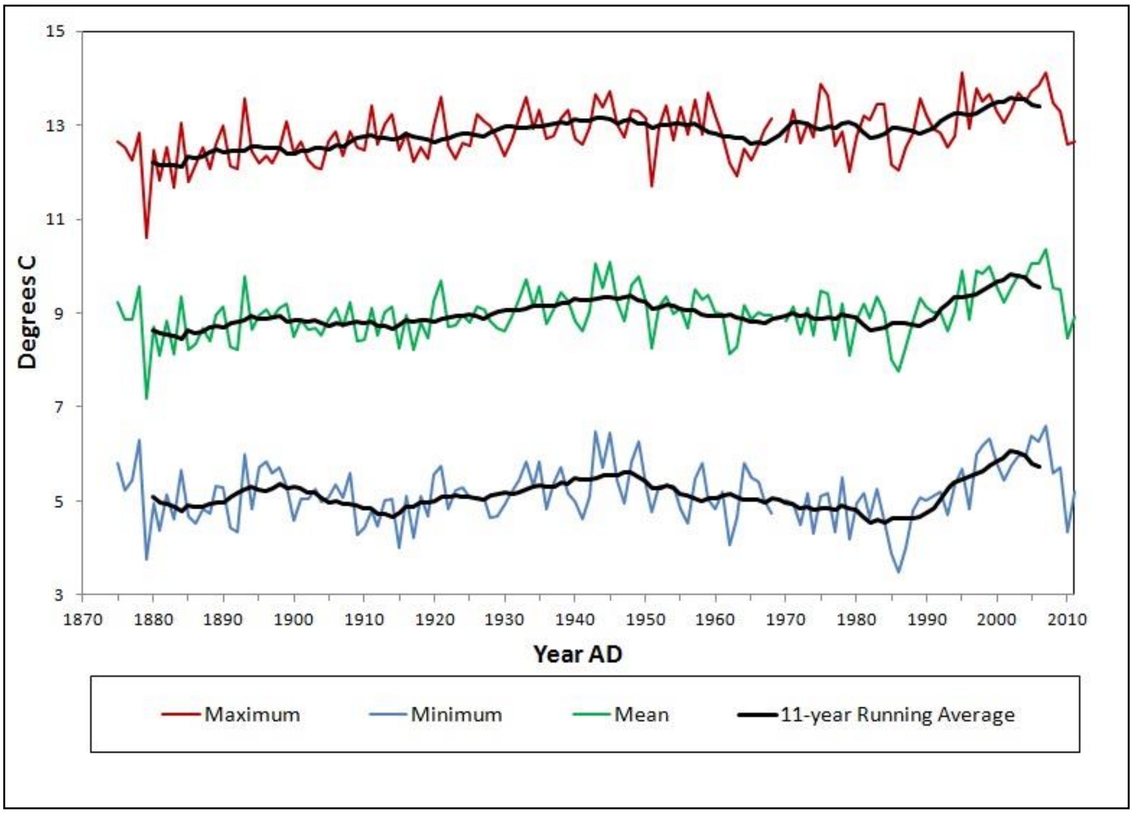


Figure 4.2 Maximum, mean and minimum annual temperatures from Markree Observatory, 1875-2011.

From an examination of Figure 4.2, a number of warming and cooling periods can be identified in all temperature categories. Eleven-year running means were used to investigate long-term trends. The maximum values display a consistent rate of temperature increase from the 1880s and continue this trend until the mid-20th century before dipping into a slightly cooler period over the 1960s. Following this downturn, maximum temperatures continue to increase steadily into the 21st century, with an accelerated rate of warming. 2010 and 2011 showed cooler maximum temperatures than have been experienced in the previous 20 years. Minimum temperatures appear to be following a slightly different pattern, and a Pearson correlation between the two series showed a weak relationship ($r = 0.41$, $p<0.05$). The minimum temperatures display more year-to-year variability in comparison to the mean and maximum values. From 1875 the minimum series displays a declining trend until 1880 before a return to warmer conditions from the mid-1880s to the beginning of the 20th century. Cooler temperatures are again experienced from 1909-1917 before a return to warmer conditions until the mid-20th century. A temperature trough from the mid-1940s until the mid-1980s is a distinct feature of the minimum series. From the late 1980s until 2009, the fastest and most substantial rate of minimum warming is evident (0.85˚C per decade). Again, 2010 and 2011 mark considerably cold years, the coldest experienced in the minimum record for 20 years.

4.2 MARKREE SEASONAL TEMPERATURE CHANGE

In an attempt to comprehensively investigate the magnitude of trends within the Markree dataset, the record was divided into seasons and examined year-to-year and on a decadal scale. Figure 4.3 shows an overall warming trend in spring, summer and winter seasons from the 1880s into the 20th century. Although autumn displays a rise in temperature from the mid-1870s until the 1900s, this rate of increase is not as notable as the other three seasons. Year-to-year variability is great in all seasons from the mid-1870s up the mid-1890s. From Table 4.1 the 1880s and 1890s are identified as the cooler decades over the Markree series in Spring, Autumn and Winter, and the 1880s represents the coldest decade on record in Spring and Autumn. In summer these two early decades are more indicative of intermediate temperatures. Overall, the four seasons exhibit a gradual warming at the end of the 19th century.

Summer and spring temperatures cool briefly at the beginning of the 20th century before they stabilise until the mid-1920s. Autumn temperatures are stable from the onset of the 20th century and remain relatively invariable until the mid-1920s. However, winter temperatures are more erratic from year to year. Winter temperatures continue to rise steadily into the 20th century before a brief cooling period is experienced in the mid-1910s. Following this cold stage, temperatures warm again into the early-1920s, before a broad scale cooling period from the mid-1920s until the mid-1960s. Temperatures increase swiftly from the mid-1960s until the mid-1970s, when a sharp but brief decline in temperatures takes place before temperatures increase into the 21st century. Furthermore, year-to-year variability becomes notably larger over this cold phase for the winter season. Autumn and spring temperatures increase progressively from the late-1920s until 1950, before a notable drop in temperatures until the mid-1980s for spring and until 1990 for autumn. Summer temperatures increase briefly from the mid-1920s unto the mid-1930s before gradually decreasing until the mid-1970s. Annual summer temperatures become more variable from the 1970s until the mid-1980s.

Spring, summer and autumn decadal temperatures from the early 20th century represent some of the coldest decades in the entire series (Table 4.1). The 1900s, 1920s and 1910s were all categorised in the top 6 coldest decades for these three seasons, and in the summer period these three decades were the coolest years on record, with the 1920s being the coldest. However, the winter season does not display the same pattern in the data, with the 1920s representing the warmest decade over the entire record, 1900s as the 5th warmest and the 1910s as the 5th coldest decade. Furthermore, winter exhibits more year to year and decadal variability over the 20th century when compared to the other three seasons, with summer and autumn showing the least variability

All seasons show accelerated warming from the mid-1980s until 2009. The fastest rate of temperature increase (0.53˚C per decade) occurs in autumn. Spring, summer and autumn temperatures are greatest in the 2000s over the entire Markree record, with winter temperatures closely following. In spring and summer the 1990s is ranked as the second warmest decade. In autumn the 1990s is ranked as the fourth warmest decade, while this decade is the third warmest in winter record. The anomalous cold spells in 2010 and 2011 broke a 30-year trend of winter warming. Summer temperatures also display a considerable downturn during these years. Spring and autumn temperatures remain similar to previous years, although in 2010 temperatures exhibit a decline.

Table 4.1 Decades ranked warmest (1) to coolest (13) for each season from Markree temperature series.

	Spring		Summer		Autumn		Winter	
	Decade	Mean Temperature	Decade	Mean Temperature	Decade	Mean Temperature	Decade	Mean Temperature
1	2000s	8.79	2000s	14.74	2000s	10.16	1920s	5.46
2	1990s	8.64	1990s	14.23	1940s	9.95	2000s	5.25
3	1940s	8.62	1940s	14.12	1950s	9.72	1990s	4.9
4	1950s	8.46	1930s	14.12	1990s	9.53	1930s	4.89
5	1930s	8.23	1890s	14.01	1970s	9.52	1900s	4.76
6	1960s	8.23	1950s	13.9	1930s	9.471	1940s	4.73
7	1890s	8.06	1980s	13.8	1960s	9.35	1970s	4.59
8	1910s	7.91	1970s	13.75	1920s	9.31	1890s	4.58
9	1920s	7.8	1880s	13.62	1900s	9.13	1910s	4.4
10	1970s	7.65	1960s	13.5	1980s	9.09	1980s	4.38
11	1980s	7.64	1900s	13.47	1890s	9.05	1880s	4.26
12	1900s	7.63	1910s	13.43	1910s	9.01	1950s	4.24
13	1880s	7.56	1920s	13.37	1880s	8.831	1960s	4.13

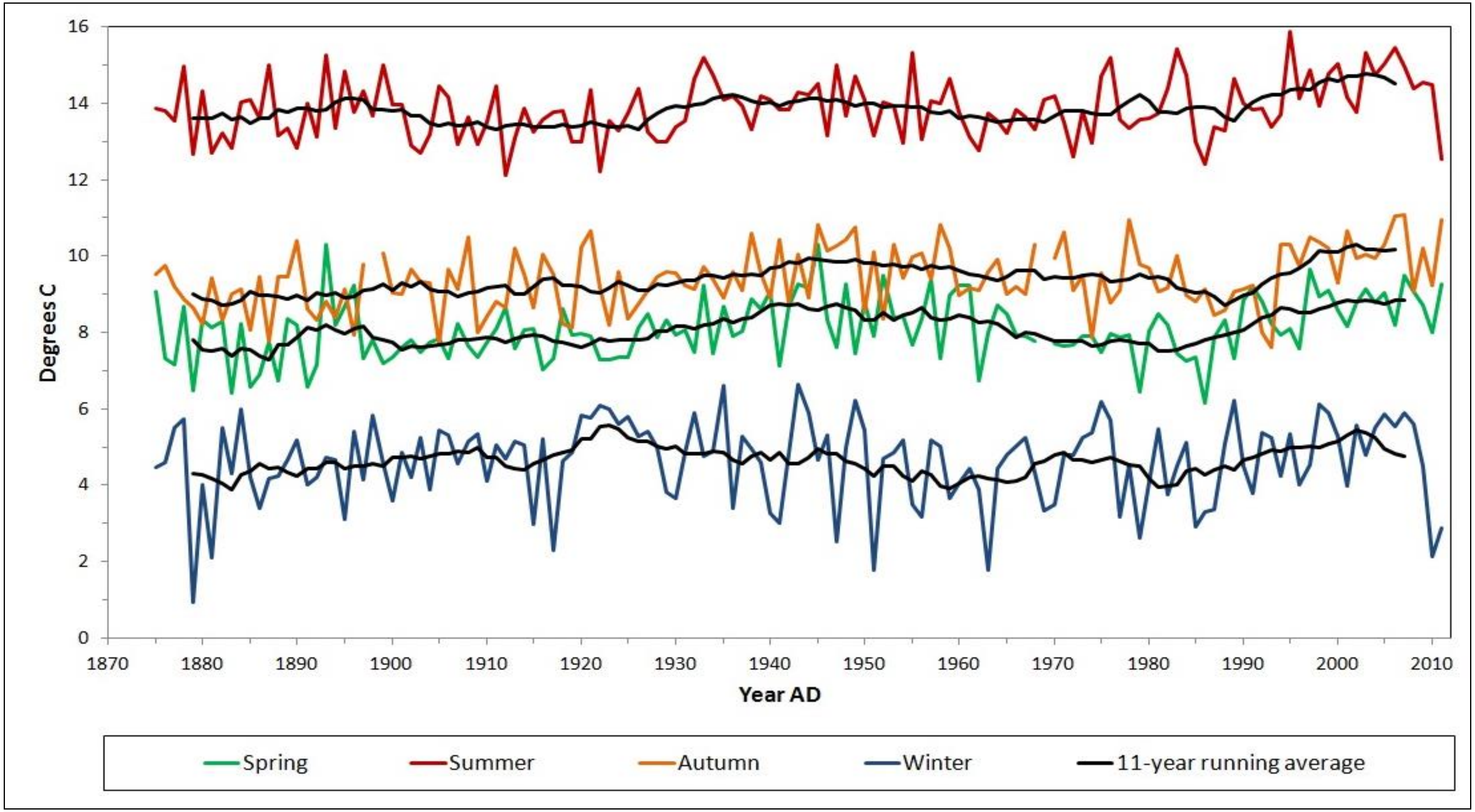
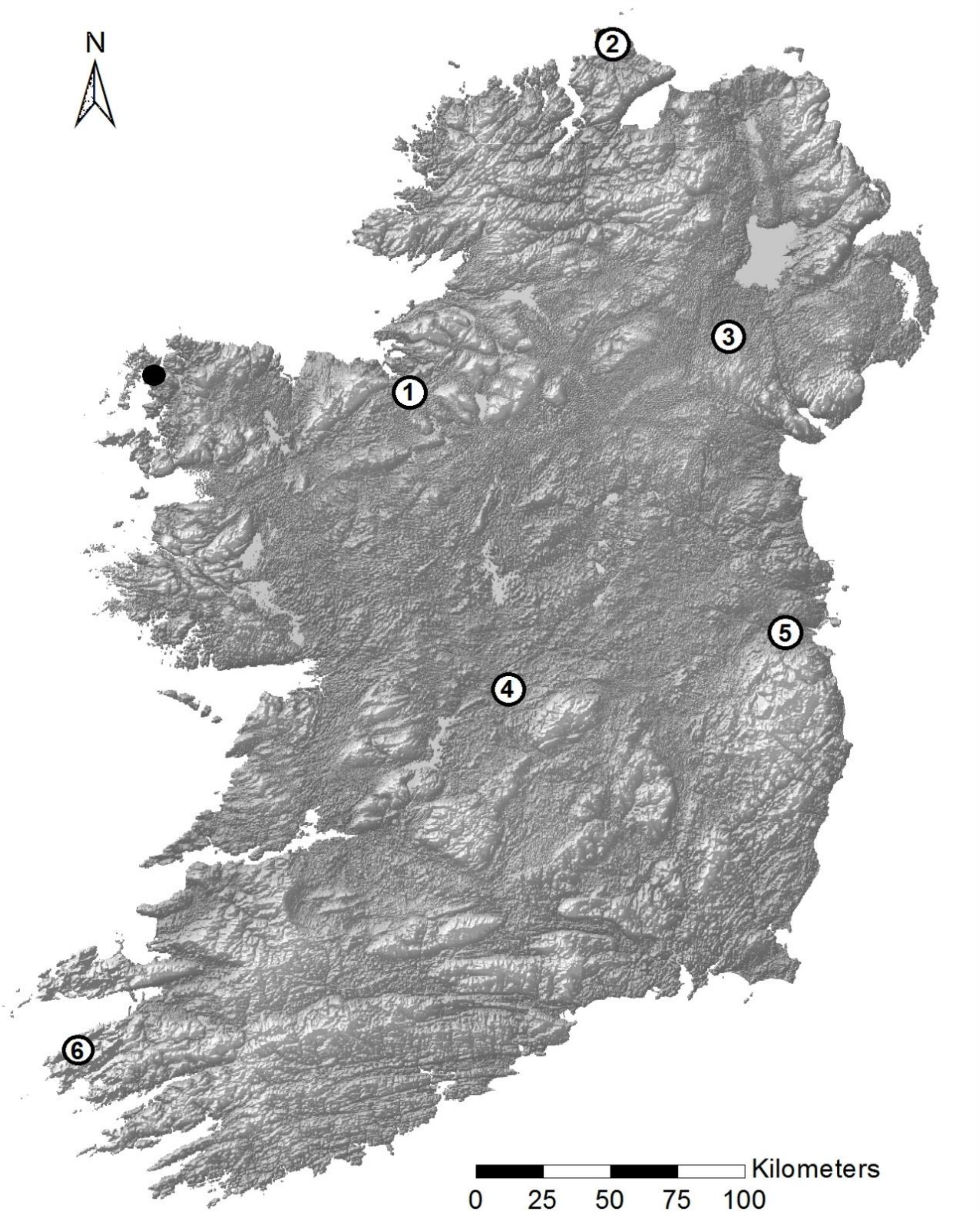


Figure 4.3 Mean seasonal temperatures from Markree Observatory, 1875-2011.

4.3 COMPARISON WITH OTHER LONG-TERM IRISH RECORDS

In order to situate the Markree reconstruction with existing Irish records, a comparison was carried out between the Markree series and the five other long-term temperature records: Armagh, Birr, Malin Head, Phoenix Park and Valentia (Figure 4.4). All information was extracted from original observers' handbooks, stored in the Met Éireann library in Dublin city, and digitised for this analysis. Daily mean values for each month are available in digital format throughout the length of each record; however, the maximum and minimum data are only available post-1950 in this format. Therefore, monthly average maximum and minimum data pre-1950 needed to be manually transferred for this study. Figure 4.5, 4.7, 4.8 and 4.9 display the 11-year running means for seasonal daily maximum, minimum and mean temperatures for each of the six temperature records. With the inclusion of Markree, the geographical spread of the six stations allows for a comparison of the various regional temperature regimes of Ireland, including the southwest (Valentia), north (Malin Head[3]), west/northwest (Markree), midlands (Birr), northeastern midlands (Armagh) and east (Phoenix Park). Figure 4.4 displays the location of each station. In addition to a graphical comparison of trends, Pearson correlations were used to compare the Markree seasonal daily maximum, mean and minimum records with the other five datasets (Table 4.2). Winter temperatures from each station were correlated with winter NAO (Hurrel, 1995) to examine any geographical trends in the NAO-temperature relationship (Table 4.3). As prolonged positive phases of the NAO generates stronger westerly wind regimes across Ireland, the frequency of westerly wind regimes were also examined for each season (Figure 4.6).

[3] In Irish literature, the Malin Head meteorological station is considered to be located in the northwest of the country, as it is located in the county of Donegal. However, as this station is located along the northern coastline and Markree itself is located along the northwestern coastline, Malin Head is considered to be a northern site for the purposes of this study (see Figure 4.4).



No.	Meteorological Station	Lat/Long	Elevation (m a. s. l.)	Years of Record
1.	Markree	54° 10' 19'' N, 08° 28' 41'' W	35	1842 - 2011
2.	Malin Head	55° 21' 09'' N, 07° 19' 55'' W	22	1890 - 2011
3.	Armagh	54° 21' 09'' N, 06° 38' 59'' W	57	1884 - 2011
4.	Birr	53° 05' 47'' N, 07° 54' 50'' W	73	1873 - 2009
5.	Phoenix Park	53° 21' 09'' N, 06° 20' 17'' W	48	1875 - 2011
6.	Valentia	51° 56' 20'' N, 10° 14' 33'' W	25	1871 - 2011

Figure 4.4 Names and locations of the six long-term meteorological stations in Ireland. Elevation in meters above sea level (m a.s.l.).

Table 4.2 Pearsons correlations between Markree and five other long-term stations in Ireland, 1875-2011.

	Winter			Spring			Summer			Autumn		
Temperature series	max	min	mean	max	min	mean	max	min	mean	max	min	mean
Valentia	0.913	0.850	0.900	0.803	0.813	0.878	0.874	0.687	0.879	0.809	0.825	0.870
Malin Head	0.826	0.799	0.870	0.819	0.707	0.837	0.874	0.668	0.820	0.834	0.767	0.860
Birr	0.884	0.816	0.912	0.899	0.795	0.837	0.875	0.726	0.820	0.910	0.877	0.940
Armagh	0.913	0.850	0.900	0.881	0.808	0.903	0.920	0.649	0.888	0.895	0.866	0.906
Phoenix Park	0.896	0.835	0.917	0.904	0.746	0.837	0.832	0.660	0.868	0.869	0.833	0.882

All correlations significant at $p<0.01$.

Table 4.3 Pearsons correlations between the winter NAO and winter temperatures for all long-term stations between 1875 and 2011.

	Markree	Valentia	Malin Head	Birr	Armagh	Phoenix Park
Maximum temperature vs. winter NAO	0.602	0.611	0.471	0.601	0.611	**0.641**
Mean temperature vs. winter NAO	**0.617**	0.611	0.441	0.587	0.611	0.593
Minimum temperature vs. winter NAO	0.569	**0.587**	0.441	0.536	**0.587**	0.508

All Pearson correlations coefficients at p<0.01.
Highest correlations in each row indicated in **bold**; lowest correlations indicated in grey.

4.3.1 Winter

In winter, three periods of warming are evident (Figure 4.5). The initial warming phase spans the 1880s to the 1920s, the second is from the 1960s to the 1970s and the final phase occurs from the mid-1980s to 2009. The only exception to this pattern occurs in maximum values for Valentia from 1880-1920 where temperatures decrease into the 1900s before a sharp increase in temperature until 1920. Valentia, located in the southwest of the country, is the only record that acts like a typical coastal station according to the classification by Smith (1976), where mean winter temperatures are on average above 6°C and the minimum values are above 4°C. Malin Head and Markree are also located in close proximity to the coast. Malin Head, at the northernmost point of the island, has slightly cooler winter minimums ranging between 3-4°C (Figure 4.5c). Markree has the lowest minimum temperatures, ranging between 0.5°C-2°C throughout its recording history. With the site located ~7 km from the coast, local topography and geographic location must be either sheltering Markree from direct oceanic influences and prevailing southwesterly winds and/or causing cold air drainage from the surrounding mountains. Armagh, Phoenix Park and Birr display similar minimum temperature ranges to Markree over their respective records. Markree displays more variability in minimum temperatures compared to all other stations, particularly in the first half of the 20th century. In the late 19th century, Markree, Birr, Armagh and Phoenix Park have similar minimum values. However, throughout the 20th century they increasingly deviate from one another. It is only in recent years that temperature values in these stations are once again following a similar pattern.

The maximum winter temperatures exhibit a similar trajectory in all stations apart from Valentia (Figure 4.5a). Temperatures in southwestern Ireland fall from the 1880s into the early 20th century. However a gradual rise is detected in all other stations from the 1880s to the 1920s. Apart from Valentia, temperatures cool in all other stations from the 1920s to the 1960s. Armagh shows the greatest rate of maximum temperature increase from the 1980s to present, with Valentia showing the smallest increase. Mean temperature patterns in all regions are quite similar (Figure 4.5b). Valentia displays the highest winter temperatures followed by Malin Head. The remaining regions are clustered together closely.

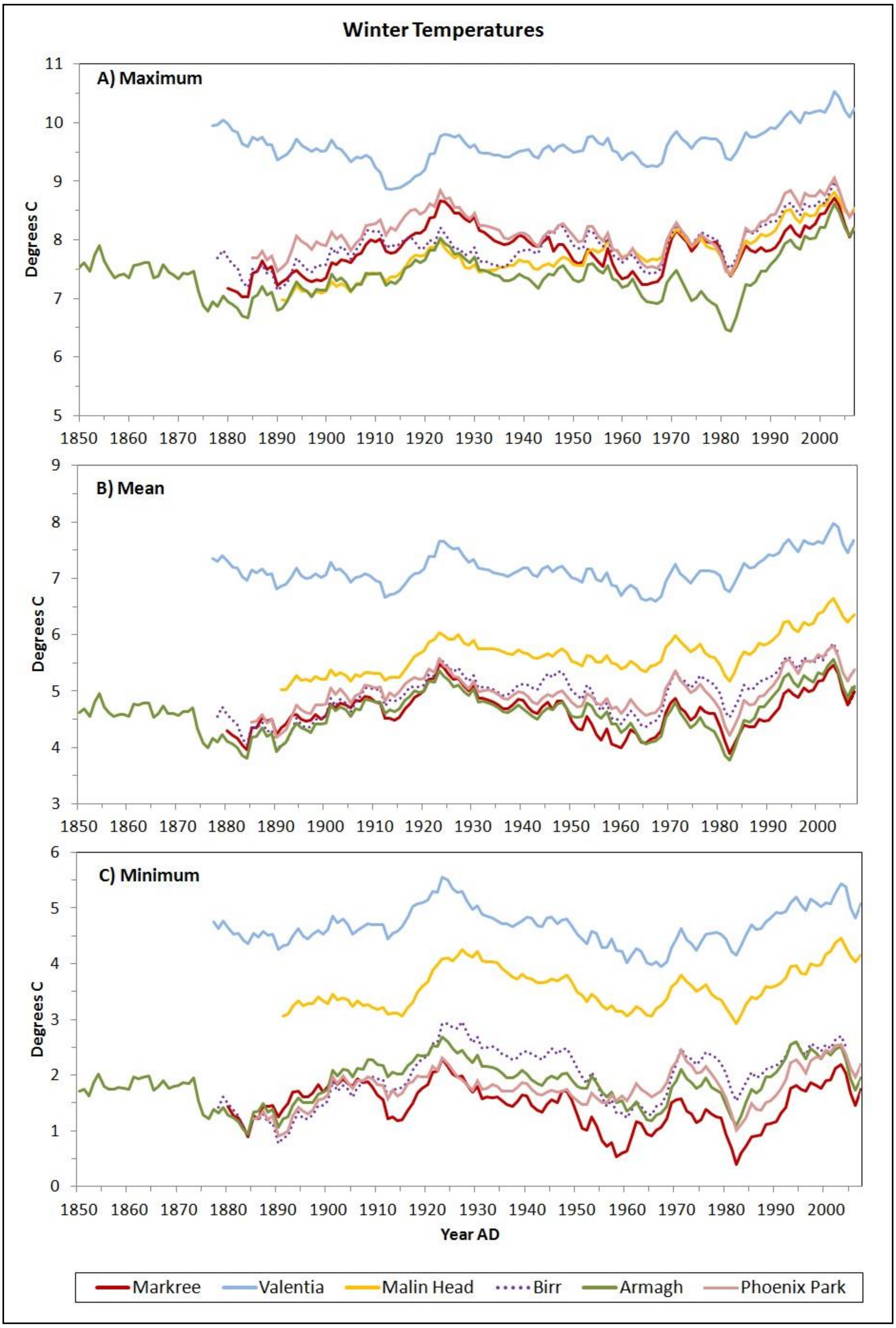


Figure 4.5 11-year running means for winter daily maximum (a), mean (b) and minimum (c) temperatures for each of the six long term meteorological stations in Ireland.

From the 1920 to the 1960s, temperature decline is greater at Markree, Birr, Phoenix Park and Armagh in comparison to those at Malin Head and Valentia, and Valentia displays the most subdued mean temperature rise from the mid-1980s to present. From the early 1940s until the early 1970s, when the NAO exhibited a continuing downward trend, maximum and minimum temperatures in Armagh, Phoenix Park, Birr and Markree decreased. However, maximum temperatures for the coastal locations of Valentia and Malin Head do not display this falling trend.

As the NAO was in decline between 1940 and 1970s, the frequencies of westerly winds were also in decline for much of this period (Figure 4.6a). As westerly winds carry warmer conditions to Ireland, a fall in the frequency of westerlies will bring about cooler winter conditions. These cooler conditions are more pronounced in inland sites, but Markree displays the greatest decrease during this time. Maximum temperatures at coastal locations such as Valentia and Malin Head are more subdued due to oceanic influences (Sweeney, 1997).

The values in Table 4.2 show the strength of the relationship between Markree and the other five stations in winter. Valentia and Armagh display the strongest relationship to the Markree maximum (r = 0.913) and minimum (r = 0.850). Birr (r = 0.912) and Phoenix Park (r = 0.917) show the greatest mean correlation to Markree. Malin Head shows the least significant relationship for the maximum (r = 0.826), minimum (r = 0.799) and mean (r = 0.870) for Markree. The relationship between NAO and winter temperatures for each record is presented in Table 4.3. Markree displays a similar strong correlation with the winter NAO when compared to the other stations, with the exception of Malin Head which shows the overall weakest NAO relationship (maximum r = 0.471; mean r = 0.441; minimum r = 0.441). Markree illustrates the strongest affiliation with the NAO in the mean values (r = 0.617), slightly higher than Armagh (r = 0.611), Valentia (r = 0.611), Phoenix Park (0.593) and Birr (r = 0.587). The strongest NAO correlation with minimum values was shown in Valentia (r = 0.587) and Armagh (r = 0.587), with Markree following closely with r = 0.569. Finally, Phoenix Park displayed the strongest relationship for maximum values with r = 0.641.

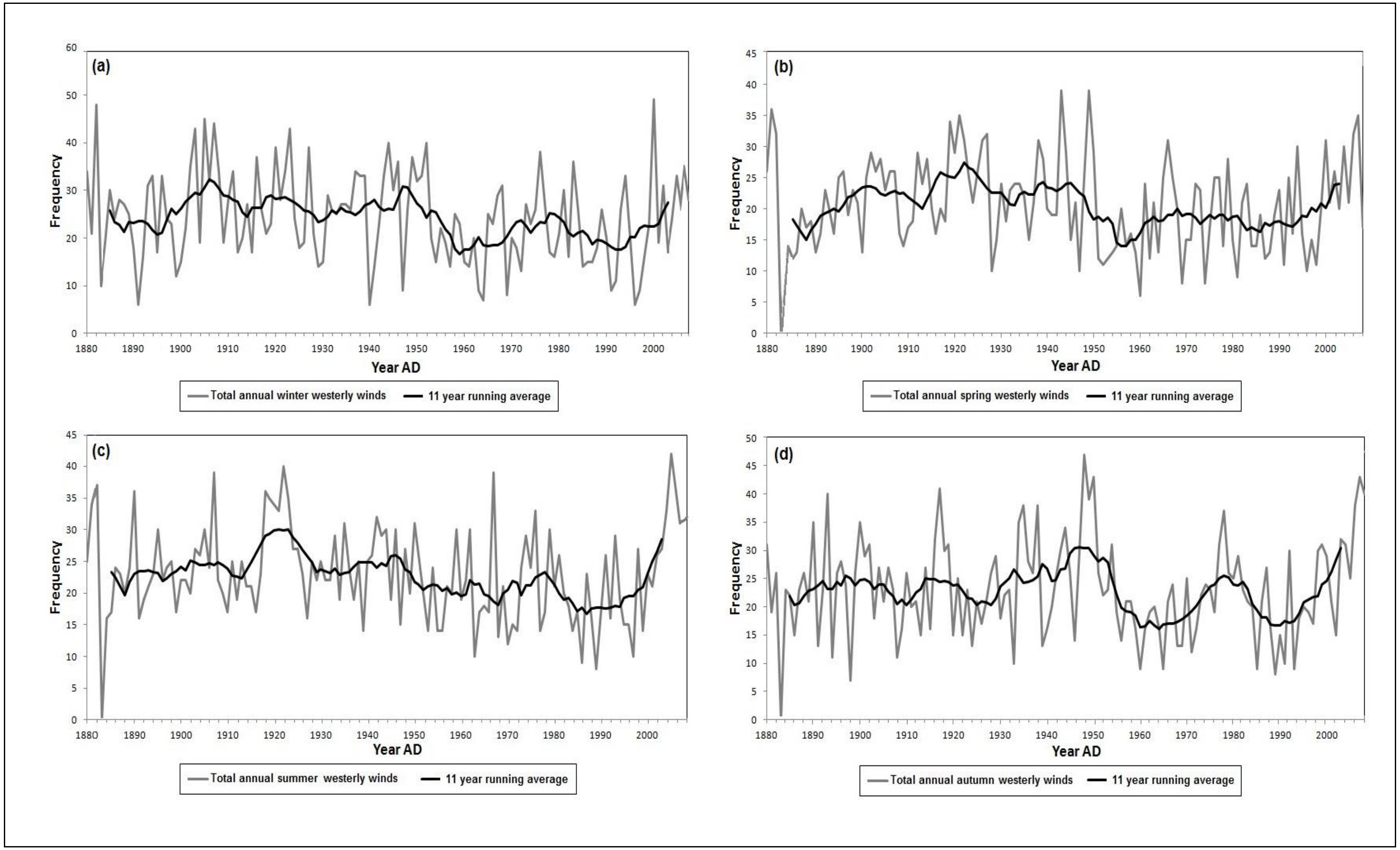


Figure 4.6 The number of days in which westerly winds were recorded in Ireland, 1880-2008, for each season (a) winter, (b) spring, (c) summer and (d) autumn.

4.3.2 Spring

Three periods of warming are evident in the spring records (Figure 4.7). The first phase commences in the 1880s into the 20th century. The next warming stage occurs from mid-1910s until the 1940s. The final and most recent rapid warming occurred from the mid-1980s until present. The most substantial spring warming in all records is experienced in the maximum values. The minimum values show more decadal variability than maximum values throughout the records. In the 1880s Markree, Birr, Armagh and Phoenix Park had almost identical minimum temperatures ranging from 3-5°C (Figure 4.7c). Valentia experienced the highest minimum temperatures (between 5.5-7.0°C), followed by Malin Head (4.8-6.3°C). Throughout the record, Markree displays the most variability with a significant decline in minimum temperature spanning the 1940s to the mid-1980s. This cooling was less severe in the other records and as a result Markree experienced the lowest minimum temperatures from the 1960s until present. Although Markree displays the lowest minimum temperature values, it has the greatest rate of minimum warming from 1980 to 1990 (1.5˚C per decade).

The maximum spring temperatures show a general increase through time in each dataset (Figure 4.7a). Malin Head displays the lowest maximum temperatures compared to the other regions, which are clustered together around a similar temperature range of 11.5-13.5°C. From 1880 to 2009, Phoenix Park and Armagh show the greatest warming of ~2°C, followed by Markree and Birr, while Valentia and Malin Head experiences the lowest rate of temperature increase over the entire record. Valentia and Malin Head display more muted changes in maximum temperatures over the length of the record compared to the more inland locations and Markree (Figure 4.7a). The more extreme sub-decadal temperature range evident at inland locations can be linked to the westerly wind regimes, with an increased frequency of westerlies corresponding with higher temperatures (Figure 4.6b).

The mean temperature record observed in Figure 7b shows Valentia experiencing warmer conditions compared to the other regions. All areas show increasing temperatures, with Markree displaying the greatest variability over the record. Decreasing temperatures from the 1940s to the mid-1980s and rapid increase into the 21st century characterise Markree’s variable nature.

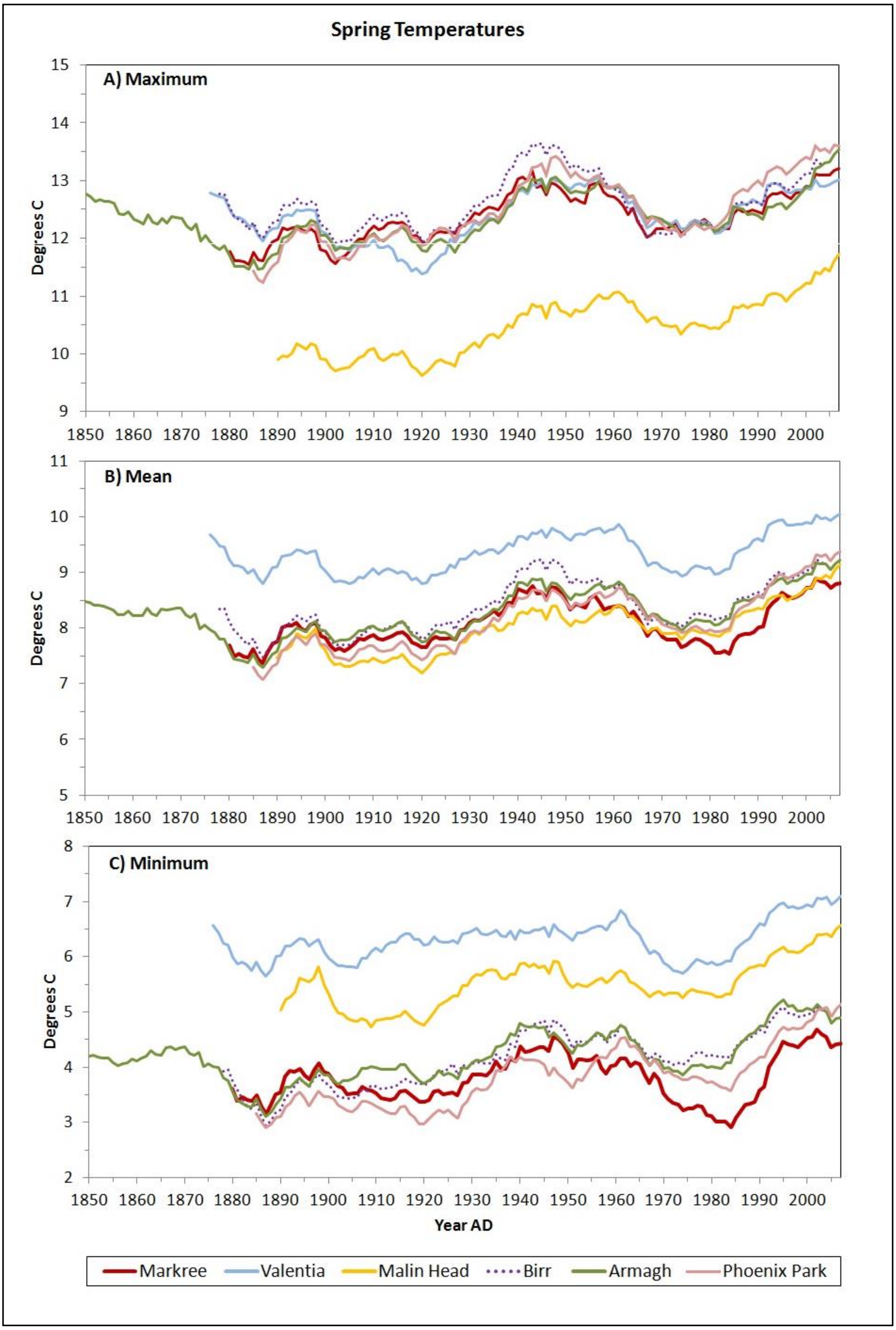


Figure 4.7 11-year running means for spring daily maximum (a), mean (b) and minimum (c) temperatures for each of the six long term meteorological stations in Ireland.

The greatest mean temperature increases in the most recent warming period were experienced in Markree, Armagh and Phoenix Park. Spring correlations displayed in Table 4.2 show mixed results. Valentia displays the strongest minimum (r = 0.813) relationship with Markree and the weakest maximum (r = 0.803) correlation. Malin Head shows the weakest relationship for the minimum (r = 0.707) and mean (r = 0.837) temperatures. Birr and Phoenix Park display the strongest maximum relationship with r = 0.899 and r = 0.904, respectively. Finally, Armagh shows the strongest relationship with Markree for the minimum (r = 0.808) and mean (r = 0.903) series. Again minimum values from the other records show the lowest correlations with Markree.

4.3.3 Summer

Warming over the length of each record for summer is not as substantial when compared to other seasons (Figure 4.8). Despite this, slight increases in temperature are still apparent in each region. Again three stages of warming are evident with the rise from mid-1880 to 1900 marking the first significant phase. A short but considerable increase is evident from the late 1920s to the late 1930s. From the 1970s until the 1990s, temperatures in the maximum values display greater inter-decadal variability compared to the minimum values. Finally, modern accelerated warming begins in the 1990s in the maximum, minimum and mean values. Valentia again displays lower minimum temperatures than the other stations, followed by Malin Head (Figure 4.8c). Markree presents the greatest variability over the length of its record including the highest rate of warming post-1990. Markree displays the lowest minimum temperatures from the 1940s until the 1970s. Warming in all regions is evident in the maximum temperature record (Figure 4.8a). From the 1960s, temperatures generally rise with a number of peaks emerging in the record.

Temperatures in all regions apart from Valentia show late 20th century warming. Valentia and Malin Head follow similar rates of sub-decadal maximum temperature variability compared to all other station locations, with the exception of the most recent warming from the mid-1980s into the 21st century. The frequency of westerlies increases from the mid-1980s to 2008 (Figure 4.6c).

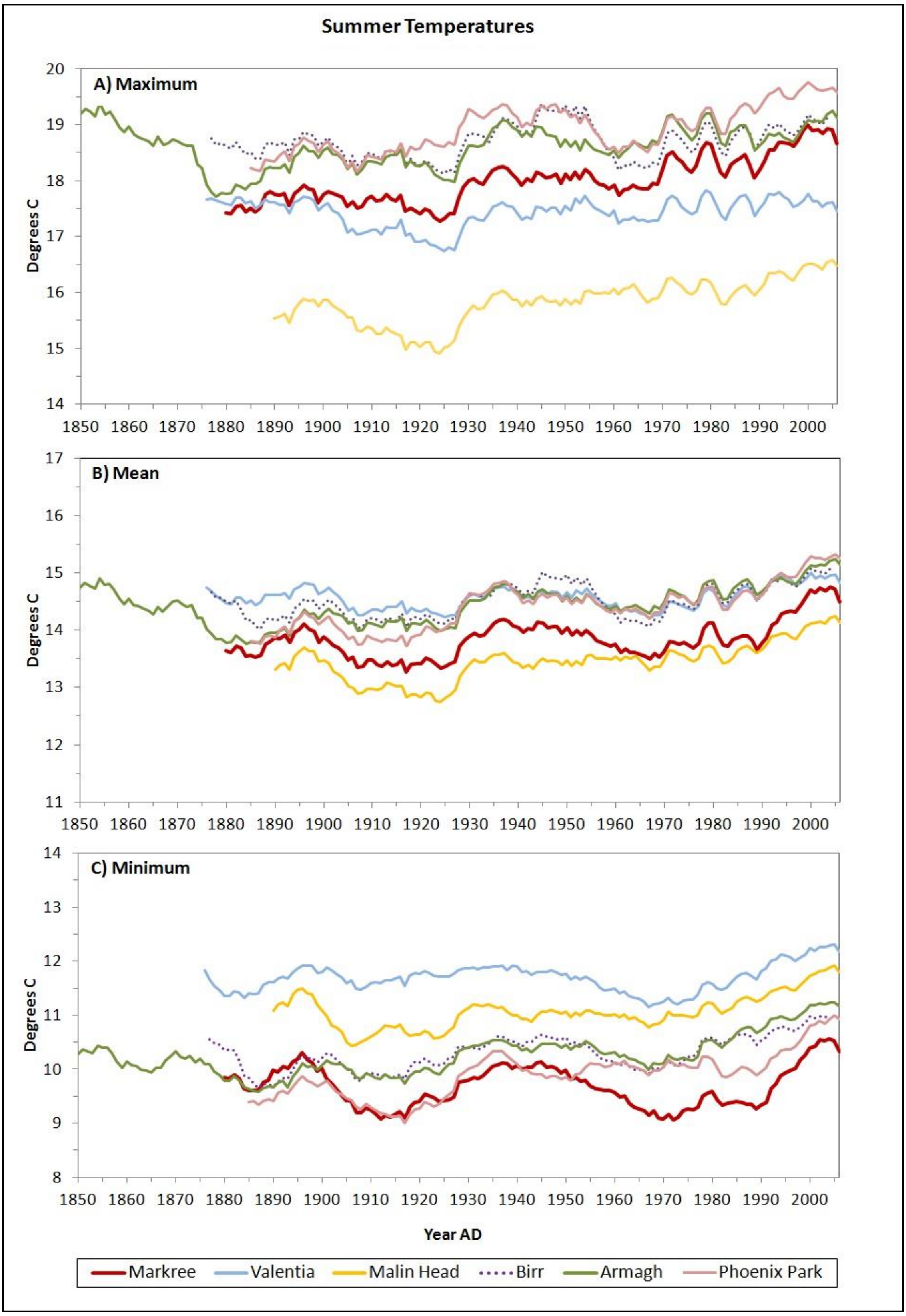


Figure 4.8 11-year running means for summer daily maximum (a), mean (b) and minimum (c) temperatures for each of the six long term meteorological stations in Ireland.

This increase corresponds with greater warming in more inland (and Markree) locations compared to the coastal areas of Malin Head and Valentia. Therefore, more inland or sheltered locations tend to exhibit a greater range in maximum temperatures through time compared to coastal regions. This emphasises the ability of oceanic influences to overwhelm the modulating control of westerly wind regimes at coastal locations in Ireland. Finally, mean summer temperatures illustrate similar ranges and patterns for each region (Figure 4.8b). Markree and Malin Head show cooler temperatures than the other regions, which are clustered together around the 14-15°C range. Markree again shows the greatest decadal variability, with more substantial cooling in the 1940s until the late 1960s and the most rapid warming from the mid-1980s into the 21st century. Malin Head and Valentia display a more subtle mean temperature increase from the mid-1980s to 2011, due to the muted increase in maximum temperatures over this time period.

The lowest correlations for all five stations to Markree is again seen in the minimum values (Table 4.2). Birr has the highest correlation with the minimum (r = 0.726) and mean (r = 0.892) series. Armagh shows the second highest correlation after Birr in the mean (r = 0.888) series and the highest maximum correlation (r = 0.920). Armagh has the lowest minimum correlation with Markree (r = 0.649). Malin Head has the lowest mean (r = 0.820) correlation and Phoenix Park has the lowest maximum (r = 0.832) correlation. Summer displays lower minimum correlations between Markree and the other five stations than any other season

4.3.4 Autumn

The greatest warming for each region over the entire chronology occurs in autumn (Figure 4.9). Two substantial warming phases are apparent. The first takes place from the 1880s until the 1940s, with the second extending from the 1990s into the 21st century. This latter period marks the fastest rate of temperature increase for any of the seasons – Markree warms at 0.11°C per decade in the maximum series and 1°C per decade in the minimum series.

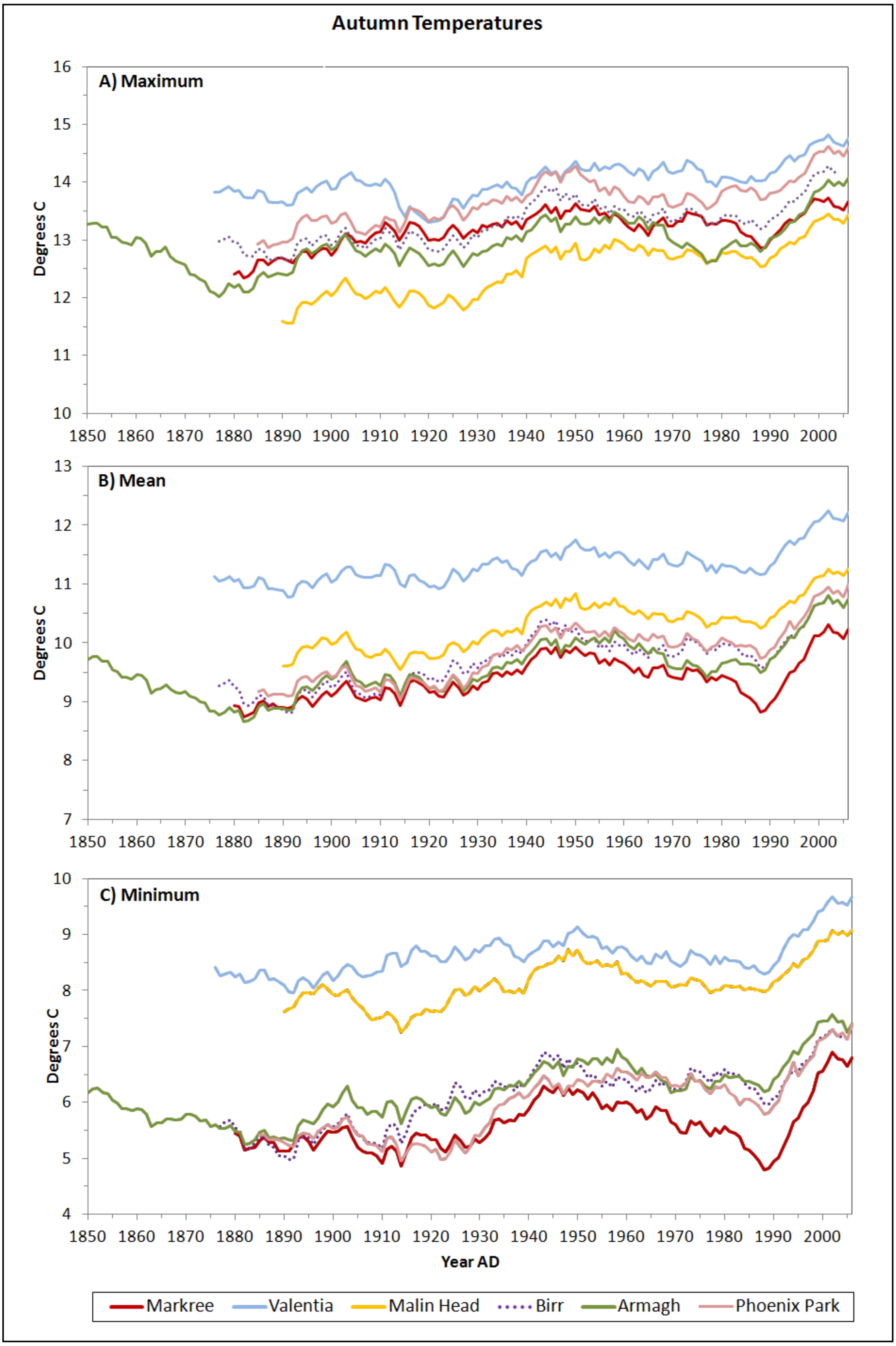


Figure 4.9 11-year running means for autumn daily maximum (a), mean (b) and minimum (c) temperatures for each of the six long term meteorological stations in Ireland.

From Figure 4.9c it is apparent that the minimum temperatures are driving the mean values, particularly from 1990 to present. Maximum temperatures from Markree, Malin Head, Birr, Armagh and Phoenix Park show notable warming from 1880 to present, while Valentia displays a slightly more muted temperature increase (Figure 4.9a). This more subtle temperature increase evident in Valentia over the length of the record may again be due to the modulating oceanic influence at this coastal location overwhelming the control of westerly wind regimes. The frequency of westerly winds in autumn appear more variable than other three seasons with a general increase from 1880s until the mid-20th century, followed by a sharp decline from 1950 to mid-1960 (Figure 4.6d).

The frequency of westerly winds increases once more from the mid-1960s to 1980, followed by a brief but notable decline until 1990; a final sharp incline in westerly winds spans the early-1990s to 2008. From the 1990s, although warming is evident in the maximum values (particularly at Armagh and Birr), the minimum record shows greater rates of temperature change. Interestingly, Valentia and Malin Head display less minimum temperature warming than other locations. It is likely that autumn westerly winds subdue the minima in exposed coastal locations. The autumn series is defined by less decadal variability and a temperature incline that includes significant modern warming over all records apart from Valentia.

The results from Table 4.2 show that the highest correlation with Markree is from Birr and Armagh, and the lowest correlations are from Valentia and Malin Head. Birr has a slightly higher correlation than Armagh for maximum, minimum and mean with r = 0.910, r = 0.877 and r = 0.940, respectively. Valentia shows the lowest correlation with maximum values (r = 0.809). Malin Head displays the lowest correlation for the minimum and mean series with r = 0.767 and r = 0.860, respectively.

4.4 SYNOPSIS

In the Markree dataset all seasons show a gradual warming trend at the end of the 19th century. Despite this warming trend, temperatures in the late 1880s were still lower than at present. In winter, spring and summer this late 19th century warming is greatest in minimum values. However, in autumn this temperature increase is more substantial in the maximum data. Apart from Valentia in winter (which has a decreasing trend) and Armagh in autumn (where minimum values display the greatest rate of warming), the rest of the stations follow quite similar patterns and rates of increase in this late 19th century data. A short cooling period in the early 20th century is evident in all records in the minimum data and this temperature decline is strongest in Markree.

Markree displays the greatest minimum warming since the mid-1980s in all seasons, particularly spring and autumn. The most recent patterns in temperature from 2010 and 2011 show a notable drop in winter temperatures. This cold spell highlights that despite a recent warming trend, extreme events can still occur. Similar cold spells are displayed over the Markree reconstruction, the coldest taking place in 1879 when the average winter daily minimum value was -3˚C. Markree's low minimum temperatures and large diurnal range are similar to inland and eastern sites such as Birr, Phoenix Park, and Armagh. Seasonal correlations between Markree and the other stations are often strongest with Birr and Armagh, and weakest with Malin Head and Valentia. This suggests that the Sligo region in the northwest of Ireland is somewhat sheltered from direct oceanic influences.

The mountains surrounding the northern and western areas of Sligo Bay (Figure 4.4), along with Markree's geographic location adjacent to the shallow Ballysadare estuary, place it well 'inland' from a southwesterly direction, likely providing shelter from the moderating westerly/southwesterly wind regimes that dominate the Irish climate. Evidence for this is seen in all seasonal minimum long-term temperature records, where Markree consistently exhibits the lowest or among the lowest values, and Valentia and Malin Head display the highest seasonal minimum temperatures. Valentia and Malin Head are also characterised by more subdued sub-decadal maximum warming and cooling throughout the record in all seasons compared to more 'inland' stations, including Markree. The Markree record consistently exhibits greater maximum and minimum temperature variability than the other five records over the past 135 years.

Interestingly, Valentia is the only location in the available long-term climate series that typically displays a regional coastal climate according to the classification by

Smith (1976). Malin Head displays the lowest spring, summer and autumn maximum values; however the minimum values are more closely related to Valentia. The NAO predictably showed a strong relationship with winter temperatures from all stations (McElwain and Sweeney, 2003), there was no discernible geographic trend except that Malin Head (on the north coast) consistently displayed the weakest relationship with winter NAO. Thus, the three coastal stations located in the north, southwest and northwest of the island (Malin Head, Valentia and Markree, respectively) all display different seasonal temperature trends, highlighting the unique regional climate regimes that exist in western Ireland. Now that it has been established that the Markree record acts more as an inland site, with a unique climatic chronology, this record can be used to assess the influence of temperature change on chironomid communities in lakes in northwest Ireland.

CHAPTER 5: LOUGH MEENAGRAUN

5.1 LAND-USE HISTORY

In recent decades, the land surrounding Lough Meenagraun and its catchment is solely used for sheep grazing under commonage practice. Here, the land is utilised equally among pastoral farmers residing in the surrounding area. However, remnants of a formerly-active sheepfold are evident around the periphery of the lake (Department of Arts, Heritage and the Gaeltacht, 2013), essentially enclosing the lake at a previous point in time. This type of enclosure was used by an individual farmer when hill improvements could not be carried out collectively. The incentive for segregating a portion of the hill was that the farmers grazing sheep would benefit from any land improvements which the farmer carried out (Hever, 1980). An article in a local newspaper, The Leitrim Advertiser, dating to Thursday, August 2nd 1894 states that "wool is one of the principal products of the neighbourhood", indicating the importance of wool production in a largely agricultural society of the late 19th century. Furthermore, evidence of population change at an Electoral District (ED) level (Figure 5.1) illustrates that the population in this area fell dramatically between 1841 (pre-famine) and 1851 (post-famine). Population fell again slightly by 1861 before increasing in the 1870s and 1880s. This increase in population in the late 19th century is not experienced in any of the surrounding EDs, each of which are marked by severe population decline. Finally, by 1900 the population of the area had declined greatly (Figure 5.1).

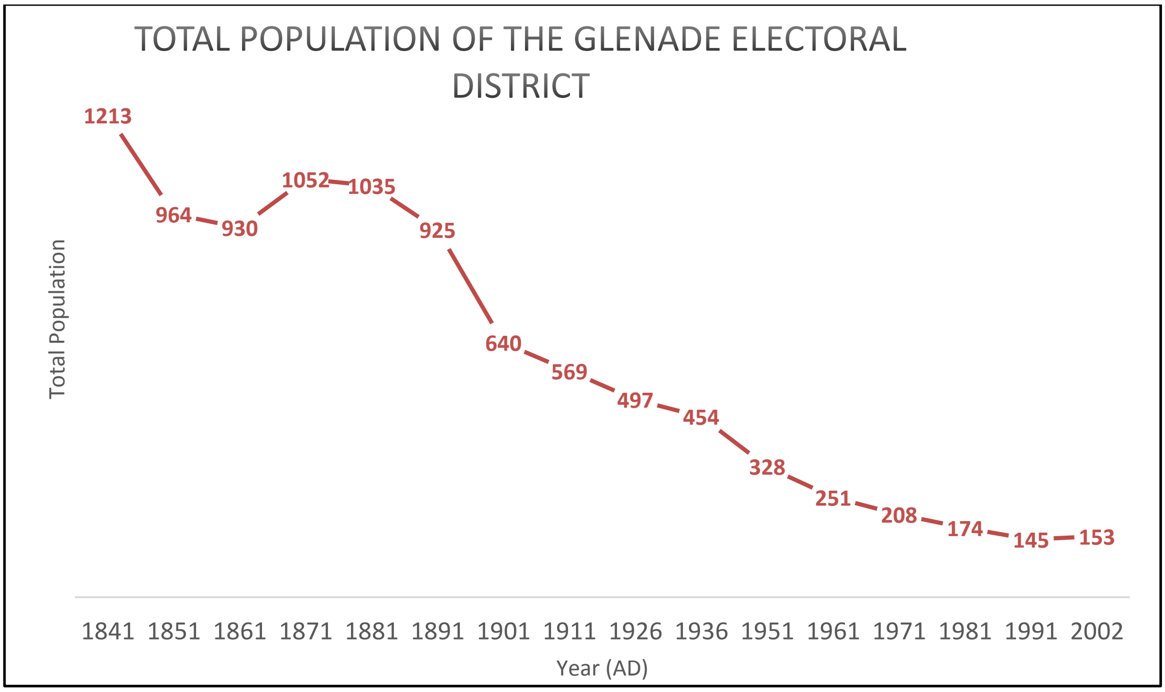


Figure 5.1 Total population change from the Glenade district (electoral district level) from 1841 to 2002.

5.2 LAKE BATHYMETRY

The bathymetric map of Lough Meenagraun is presented in Figure 5.2. The lake has an oval asymmetrical shape with notable shelves on the northern, southern and southeastern sides, marking the littoral zones. The deepest section of the lake is 2.1 m, and the sediment cores were extracted from this sector of the lake. The transition from the deepest profundal zone to the littoral layer is steepest on the eastern and western sections of the lake, while less severe slopes are evident on the northern, southern and southeastern areas. On the southeastern shelf, the morphology of a previously active small (< 0.5 m wide) outlet stream is evident. The rocks and boulders along the southeastern shelf essentially damn the outlet channel. The angular nature and 'fresh' surface of the boulders makes it unlikely they were deposited in situ during the last Ice Age. Rather it is likely that their placement was altered by humans sometime in the recent past.

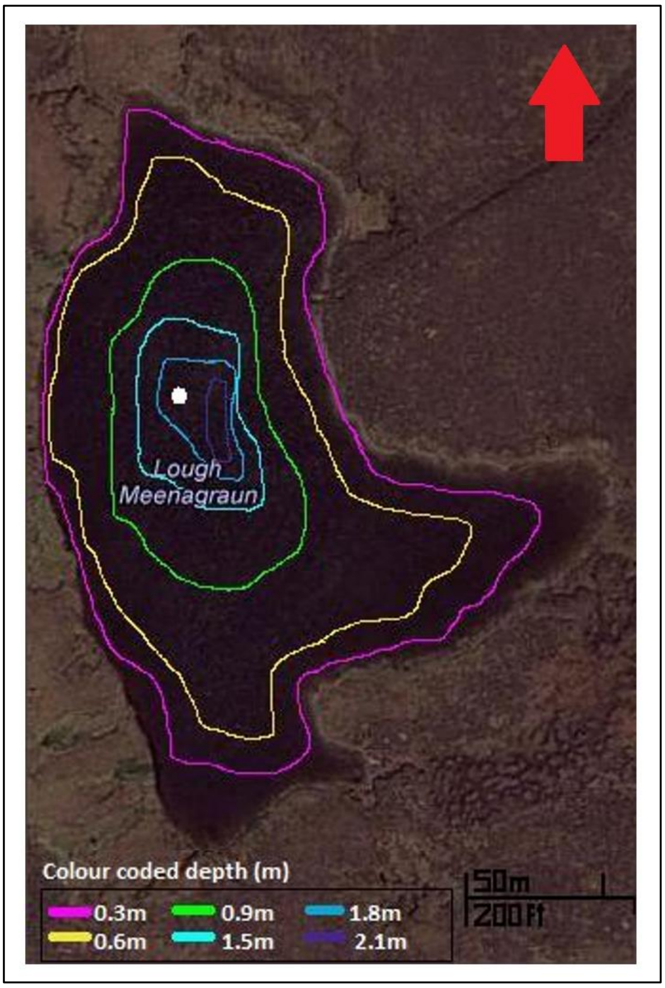


Figure 5.2 Bathymetric map of Lough Meenagraun. White circle marks point where sediment cores were extracted.

5.3 LAKE SEDIMENT CHARACTERISTICS AND LOI

Two replicate cores were recovered from centre of Lough Meenagraun, just off the deepest section. They were uniform in appearance, both consisting of dark brown gyttja with unconsolidated sediment in the upper 6 cm. The first core was 27 cm in length, while the second was 26 cm. The longer core was designated the master core and the sediment from this core was used for radiometric dating, LOI and chironomid extraction. LOI from this core is presented in Figure 5.3. Inorganic carbon (LOI 950˚C) remains consistently low and stable over the length of the sediment core. Organic carbon (LOI 550˚C) values range from 27% to 91%. Values remain relatively low towards the bottom of the core, with a gradual incline until 12 cm. The level of organic carbon abruptly increases at 12 cm until it stabilises at 8.5

cm. Organic carbon remains at around 85% until a slight dip at 5 cm, where values decline to ~ 75%, and stabilise for the remainder of the core.

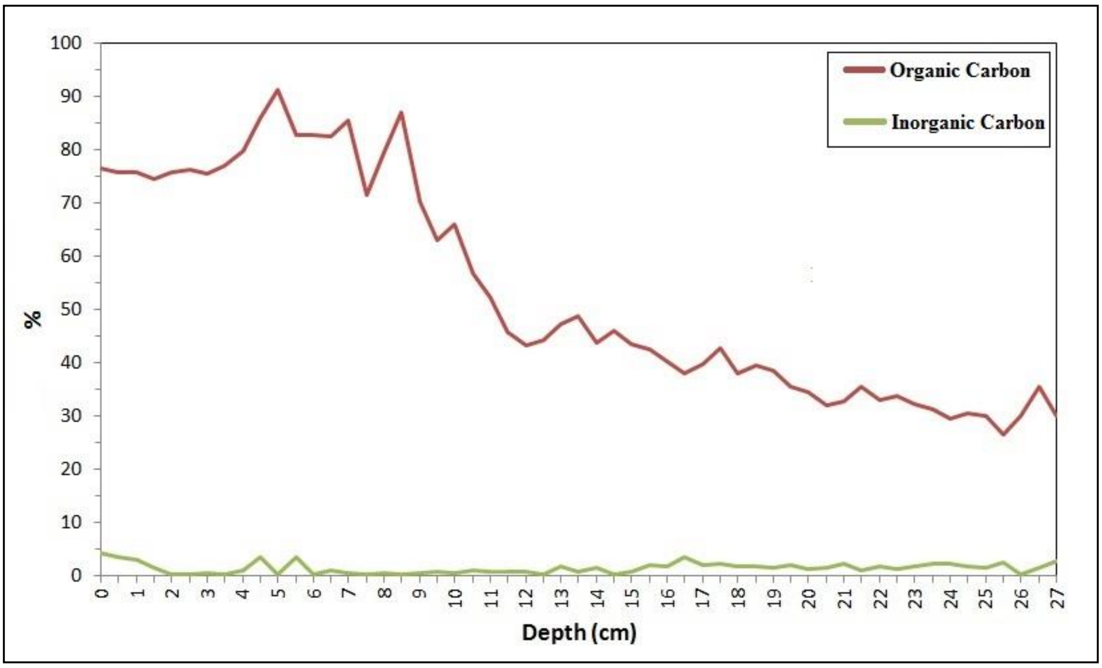


Figure 5.3 Organic and inorganic content for the entire sediment core of Lough Meenagraun.

5.4 DATING MODEL

Establishing sediment chronologies and determining uncertainties is vital in palaeolimnological research. The level at which the sediment record can be compared with instrumental data depends on the sensitivity of the proxy indicator, the rate of sediment accumulation, and the accuracy of dating chronology.

5.4.1 ^{210}Pb Chronology

Due to its short half-life ^{210}Pb can date sediment reliably to around AD 1850 (Appleby, 2013). The top 8.5 cm section of core A was datable by ^{210}Pb and represents 1860 to 2009. The results of the ^{210}Pb age depth model are displayed in Figure 5.4.

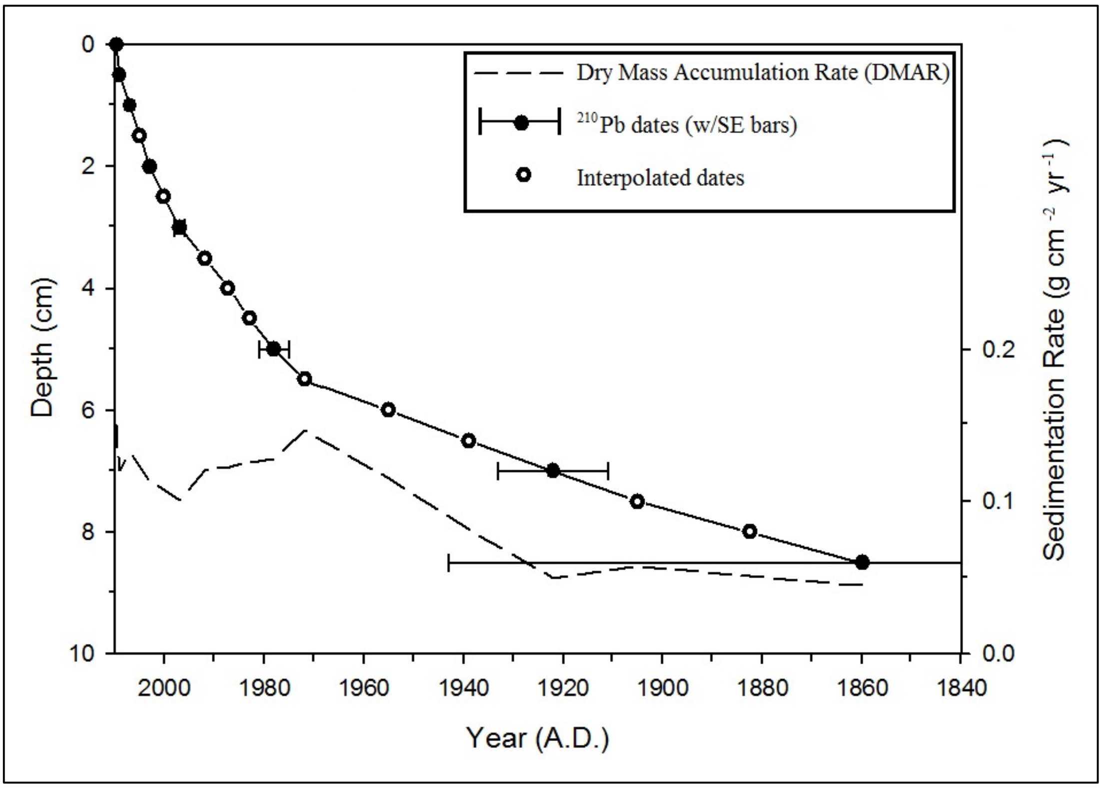


Figure 5.4 ^{210}Pb age-depth model for Lough Meenagraun utilising the CRS (constant rate of supply) model.

Standard errors (SE) of ^{210}Pb dates ranged from 83 years at the bottom of the chronology to approaching zero error at the top of the core. SE of ^{210}Pb dates for the time period of comparison with the instrumental record (1880 to 2009) ranged from 20 years (at the bottom of the chronology), 5.5 years (after 1975) to approaching 0 years at the top of the core. The mean dry mass accumulation rate (DMAR) varied over the core from the mid-19th century to present. From 1860 up until 1922 the lake was characterised by a steady low dry mass accumulation rate of 0.033 g cm^{-2} yr^{-1} (3 yr cm^{-1}) before a notable increase to 0.15 g cm^{-2} yr^{-1} (7 yr cm^{-1}) from 1922 until 1972. Although the dry mass accumulation rate is high in the modern section of the core, the sedimentation rate falls by 0.04 g cm^{-2} yr^{-1} (25 yr cm^{-1}) between the mid-1970s and 1997, From the late 1990s until 2009, the rate of sedimentation falls by 0.086 g cm^{-2} yr^{-1} (12 yr cm^{-1}). Overall, the ^{210}Pb chronology exhibits no significant irregularities, indicating that no significant slumping has occurred.

5.4.2 ^{14}C Dating Problems

Two AMS radiocarbon dates of the humic acid fraction of bulk sediment were obtained for Lough Meenagraun. A sample for ^{14}C dating was taken from the bottom of the core and another sample was taken just below the ^{210}Pb-dated section. The sample taken from the middle section of the core (12.5-13 cm) was found to be older than the sample from the bottom section of the core (26.5-27 cm). As the lake is bordered by bog, it is likely that the peat material from the surrounding catchment is entering the lake. This sediment contains already partially decayed ^{14}C humic acid compounds, essentially contaminating in-lake sediment layers by reworking older material through newer sediments (Watson *et al*., 2010). This essentially distorts the levels of ^{14}C within lake sediments (Shore *et al*., 1995). Subsequently, ^{14}C dates were deemed unreliable and were not used for further analysis.

5.5 TEMPERATURE DATA LOGGERS

The collection of water temperature data at the site was unsuccessful as the data logger was removed by an unknown source during the first year of data collection. Hourly air temperature data was collected. Although placed in the shade, the air temperature data logger was likely exposed to sunlight, and as a result the data are slightly skewed. Despite the problems encountered with the collection of air temperature, trends can still be inferred from the dataset for this site. Mean daily air temperature was calculated from the average of the 24 hour readings over the entire recording period of two years (Figure 5.5). Temperature for the months of June, July and August in 2010 and 2011 reached an average of ~12˚C.

Temperatures recorded by the data logger between April 2010 and September 2010 were compared with those from the Markree record over the same period (Figure 5.6) to determine the agreement between these two datasets. Mean daily air temperature recorded using the data logger was slightly lower (~1ºC between April-September 2010) than that at Markree Observatory, which is slightly warmer than expected (likely due to exposure to sunlight). The elevation difference between the Lough Meenagraun site (379 m a.s.l.) and Markree station (35 m a.s.l) was used to estimate the temperature difference between the two sites using local lapse rates (cooling of 0.0074°C m^{-1} elevation (Goodale *et al*., 1998)). The Lough Meenagraun site was estimated to be 2.65°C cooler than Markree site. Despite the problem with shielding direct sunlight, daily fluctuations in the daily maximum, minimum and mean Markree records and the air temperature data recorded at this lake site are largely synchronous over the time period of recording.

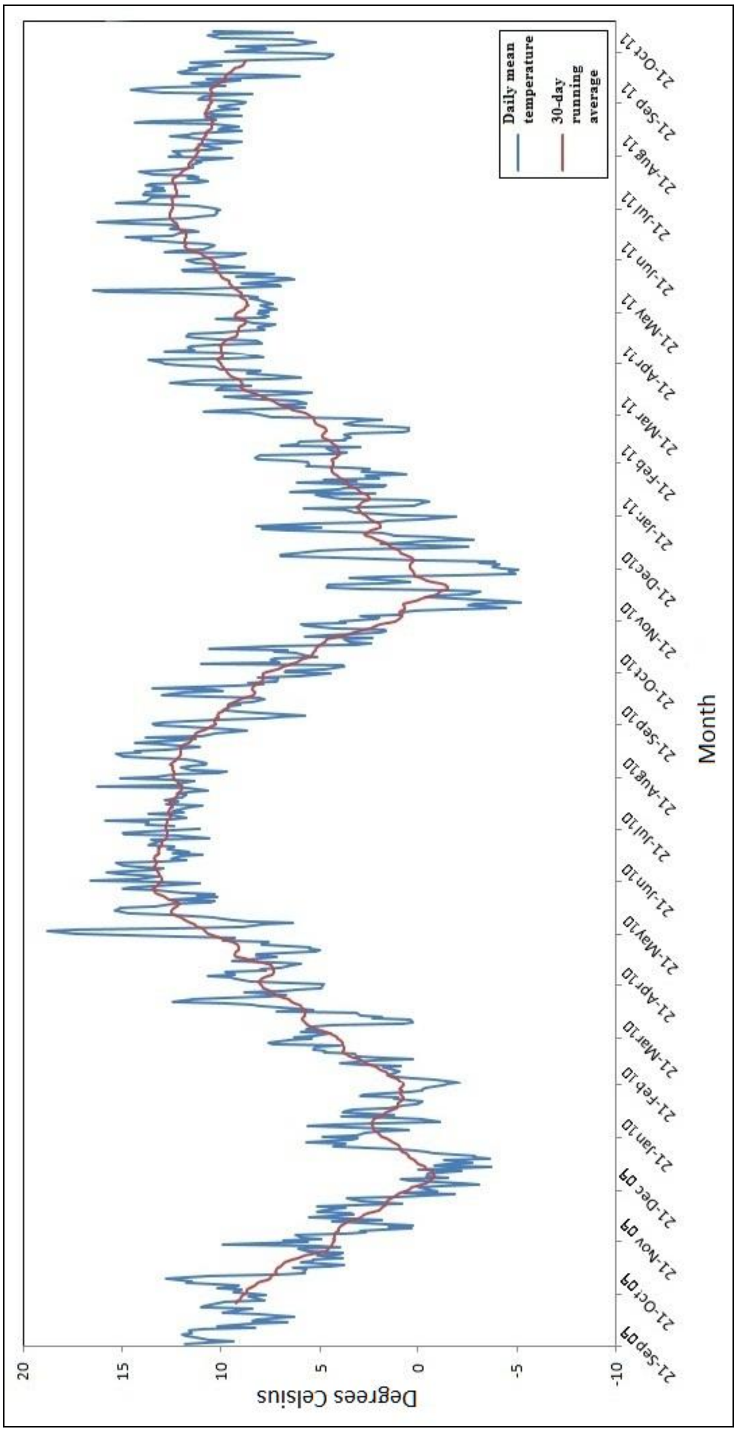


Figure 5.5 Mean daily air temperatures calculated from the average of the 24 hour readings over the entire recording period of two years collected using an air temperature data logger.

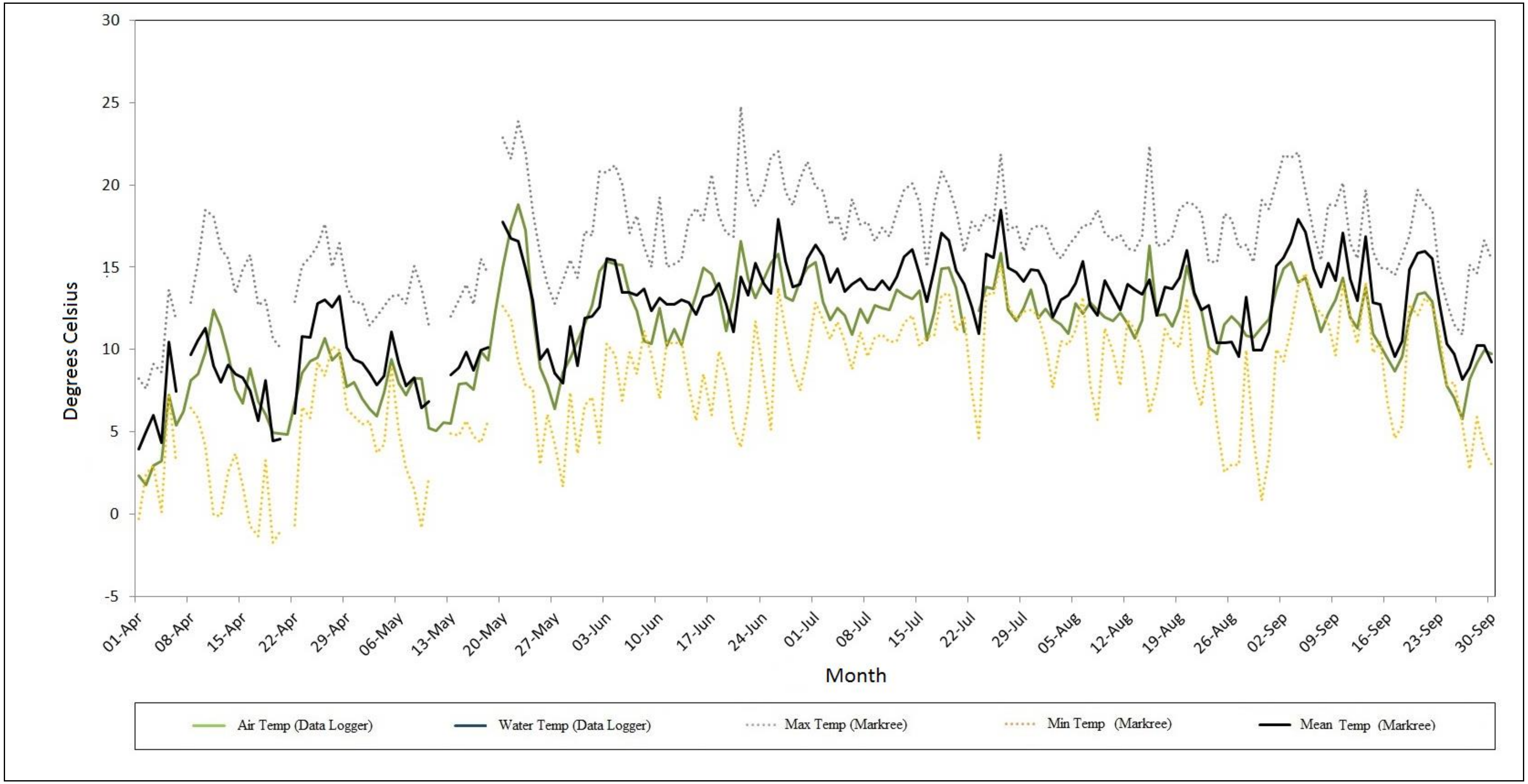


Figure 5.6 Daily mean air temperatures recorded from April 2010 to September 2010 compared with the daily maximum, minimum and mean temperatures from the Markree record over the same period.

5.6 CHIRONOMID COMMUNITY COMPOSITION

The results from the chironomid stratigraphy will be reported firstly from the entire core and secondly from the ^{210}Pb-dated portion. The dated section of the stratigraphy will be examined independently as the ^{210}Pb age-depth model extends to 1868, and therefore, the chironomid-inferred temperatures from these layers can be directly compared with the Markree Observatory temperatures record and historical human impacts. A stratigraphic diagram of the complete core with important chironomid taxa is presented in Figure 5.7. In total, 41 taxa were identified from the Lough Meenagraun core, with an average of 21 taxa per sample. Common taxa were identified as those present in at least two samples with a relative abundance of 2% in at least one sample. Ten taxa were deemed 'rare' in the core in that they did not meet the above criteria. In most samples the head capsules were well preserved, but concentrations varied greatly throughout the core. Overall head capsule concentrations ranged from 20 to 104 head capsules per ml of wet sediment, with a minimum of 50 chironomids enumerated for every sample. The Shannon-Wiener diversity index ranged from 2.9 to 4.9, with the lowest diversity levels at 3.5-4.0 cm depth and the highest diversity at a depth of 8.5-9 cm. Species diversity shows variability from the mid-19th century to present (9.5 cm-top of core), with lowest diversity at 1990 (3.5 cm). Diversity does not change in line with head capsule concentration. Zonation was based on sum-of-squares partitioning and significant zones were determined using BSTICK model (Bennett, 1996). Zonation for the entire core was significant at two zones, with a boundary occurring at 9.5 cm depth, just before the ^{210}Pb-dated portion of the core.

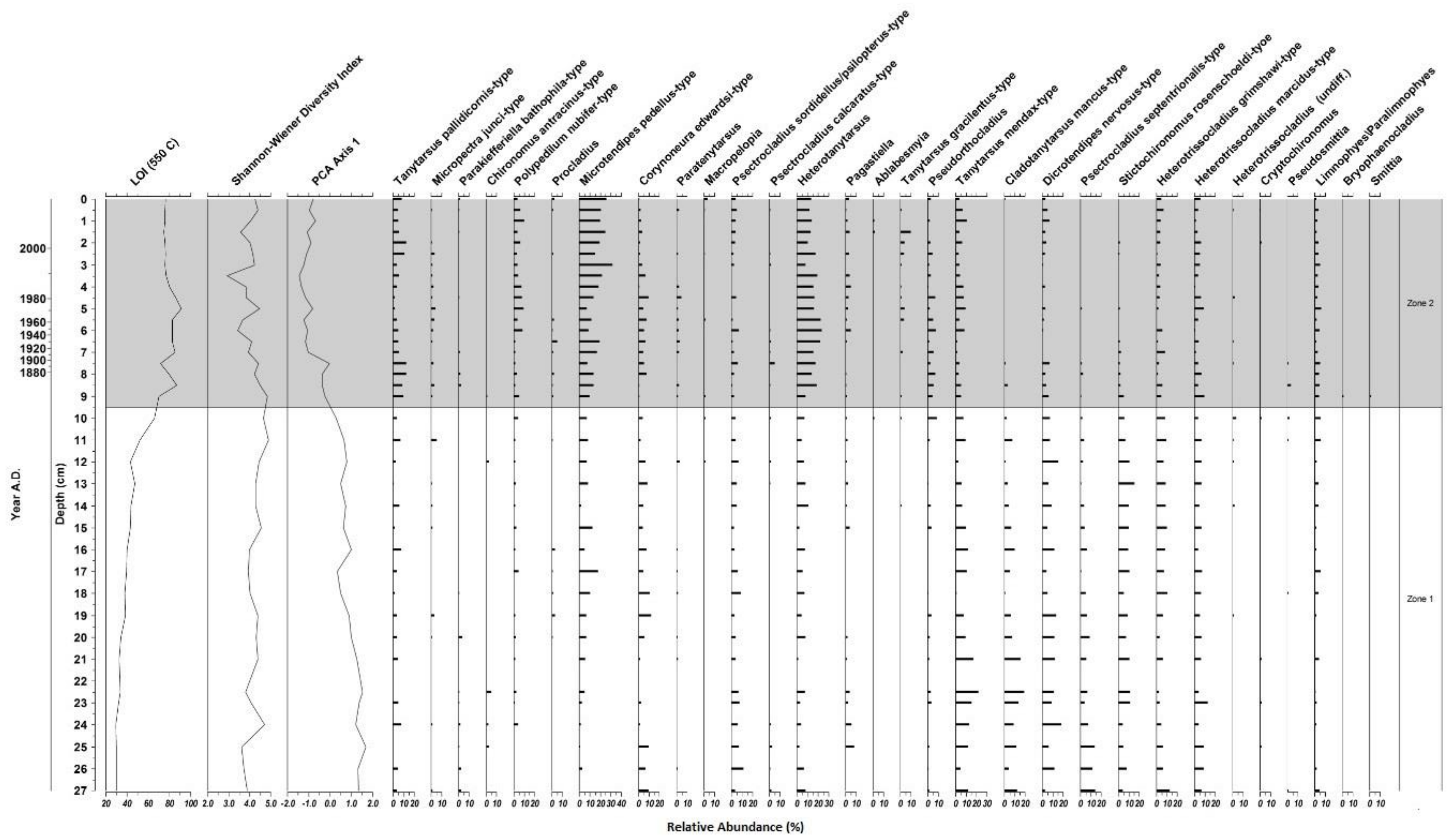


Figure 5.7 Chironomid stratigraphy of important chironomid taxa and community zonation for Lough Meenagraun. LOI (550˚C), Shannon-Wiener Diversity of each sample, Axis 1 scores from Principal Component Analysis (PCA) of chironomid data, and summer air temperatures inferred using Potito *et al.* (forthcoming) transfer function with LOESS smoother (span = 0.2).

While taxa ecology based on Wiederholm (1983), Rieradevall and Brooks (2001) and Brook *et al*. (2007) offered valuable information at genus, sub-genus and species level, it was essential to examine ecological preferences of taxa within an Irish context. The chironomid taxa identified in the Irish training set (Potito *et al.*, forthcoming) are well represented down-core in Lough Meenagraun. Consequently, ecological optima and tolerances established for each taxa in this Irish training set were used to further determine ecological preferences (see Appendix A.1).

5.6.1 Zone 1 (27 cm – 9.5 cm)

In the Lough Meenagraun stratigraphy, zone 1 is marked by the highest level of taxa indicative of cool, unproductive lake conditions (Figure 5.7). *Stictochironomus rosenschoeldi*-type (9%), *Heterotrissocladius grimshawi*-type (8%), *Heterotrissocladius marcidus*-type (7%) and *Psectrocladius septentrionalis*-type (6%) comprise ~31% of the head capsule concentration in this zone. Warm water taxa are also present in large numbers in this zone, comprising 32% of total chironomid community. These include *Tanytarsus mendax*-type (10%), *Dicrotendipes nervosus*-type (10%), *Cladotanytarsus mancus*-type (8%), *Pseudorthocladius* (2%) and *Pagastiella* (~2%). Taxa associated with bog/acidic lake waters comprise ~25% of the midge community in zone 1. *Psectrocladius calcaratus*-type (7%), *Heterotanytarsus* (6%) and *Psectrocladius sordidellus/psilopterus*-type (6%) are the most dominant taxa associated with acidic water conditions. In the Irish training set *Heterotanytarsus* is strongly associated with lakes situated in bog areas (Potito *et al*., forthcoming). Taxa indicative of more eutrophic lake conditions are also present in zone 1 reaching levels of ~13.5%. *Microtendipes pedellus*-type (6.5%), *Tanytarsus pallidicornis*-type (4%) and *Polypedilum nubifer*-type (2%) make up this group and are also linked with eutrophic lakes in the Irish training set (Potito *et al*., forthcoming). Head capsule concentrations average ~21 capsules ml^{-1} in this zone, while diversity index averages ~4.2.

5.6.2 Zone 2 (9.5 cm – top of core)

Taxa associated with eutrophic lake conditions become more dominant in this zone, reaching an average level of 39%. *Microtendipes pedellus*-type (17%), *Parakiefferiella bathophilia*-type (6%) and *Polypedilum nubifer*-type (5%) and, to a lesser extent *Micropsectra junci*-type and *Procladius* show the greatest increase in numbers in between zone 1 and zone 2. Throughout this zone, these taxa display minor variability in percentage abundance. *Heterotanytarsus* which is associated with the littoral zone of humic water lakes, increases from 6% in zone 1 to 16% in zone 2. Taxa indicative of bog environments represent 25% of the of the chironomid community in zone 2.

A decline in the percentage of taxa linked with cooler, less productive lake conditions is notable in this zone, dropping to levels of ~10%. *Psectrocladius septentrionalis*-type and *Stictochironomus rosenshoeldi*-type are present in low numbers at the beginning of zone 2 and notably decrease by the early 20th century (7.5 cm depth). *Heterotrissocladius grimshawi*-type and *Heterotrissocladius marcidus*-type persist in this zone but experience a drop in percentage from zone 1 to levels of 4% and 5% respectively. Thermophilous taxa such as *Tanytarsus mendax*-type, *Dicrotendipes pedellus* type and *Cladotanytarsus mancus*-type all show a notable decline in percentage abundances. Conversely, some warm water taxa such as *Tanytarsus gracilentus*-type and *Pseudorthocladius* show minor increases in this zone. *Bryophaenocladius* and *Smittia*, both associated with terrestrial environments, emerge for the first time in the stratigraphy. Cranston *et al*. (1982) suggest that the presence of *Bryophaenocladius* in lake sediment may be indicative of erosion events. Species diversity becomes more variable throughout this zone with an average of ~4.0. The concentration of head capsules increases to an average of 27 head capsules ml^{-1}.

5.6.3 Community Compositional Change

The transition from zone 1 to zone 2 can be seen as a shift to the left along PCA Axis 1 (λ = 0.414) on the bi-plot (Figure 5.8). The shift can be explained by a transition from taxa associated with cool, oligotrophic conditions to taxa linked with warmer, eutrophic and more acidic lake conditions. Here, *Psectrocladius septentrionalis*-type, *Stictochironomus rosenschoeldi*-type are located to the right of the bi-plot and *Microtendipes pedellus*-type, *Polypedilum nubifer*-type and *Heterotanytarsus* are positioned to the left (Figure 5.9).

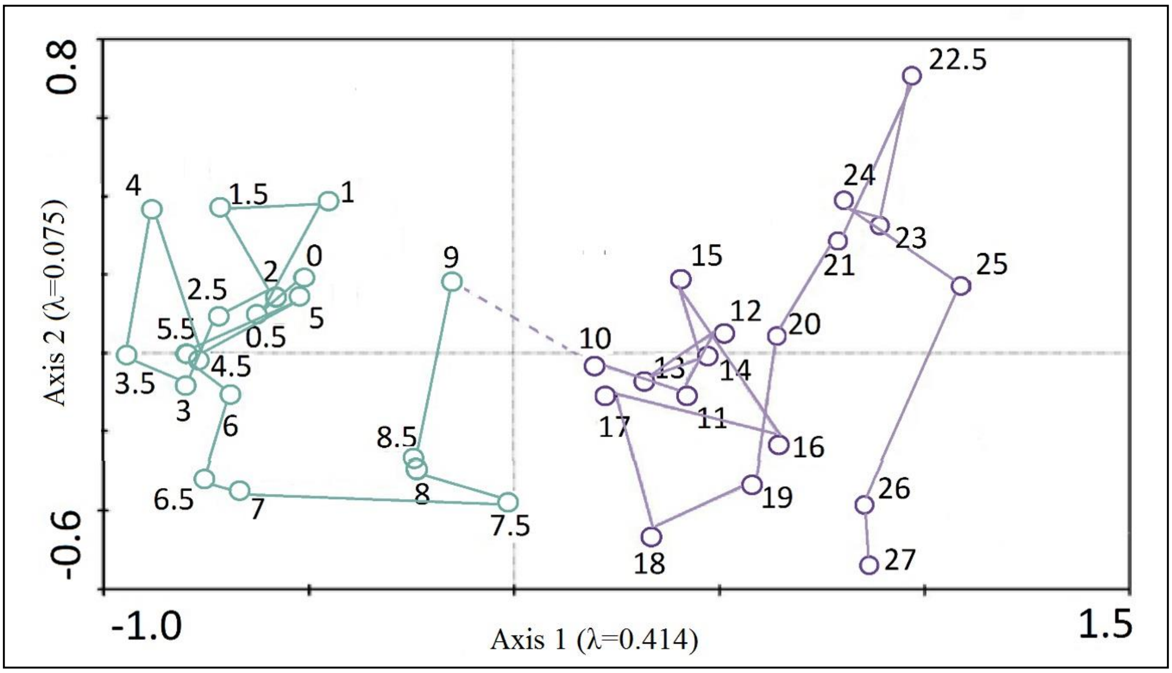
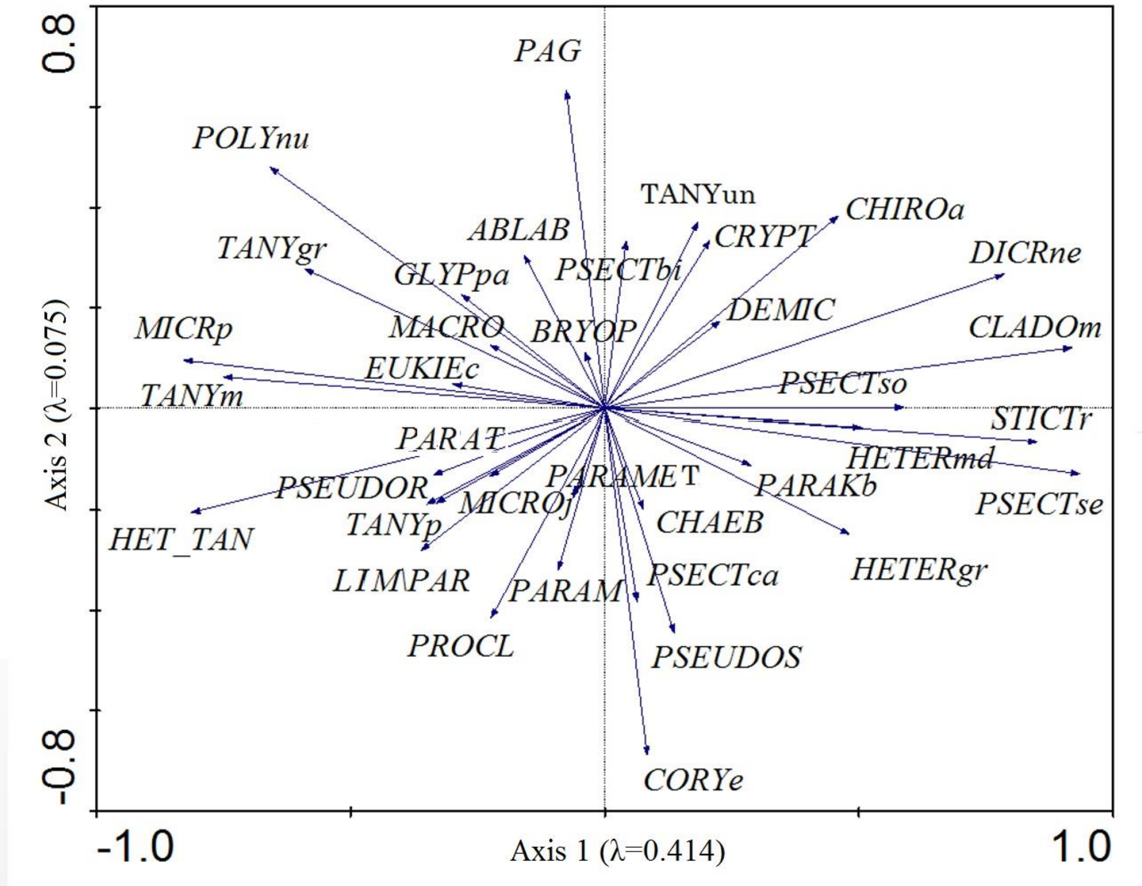


Figure 5.8 Principal component analysis (PCA) bi-plot for chironomid samples displaying changes in chironomid trajectory (chironomid zones from Figure 5.7 are highlighted in different colours on this graph). Circles indicate different depths (cm).



Legend

Code name	Taxa full name	Code name	Taxa full name
ABLAB	*Ablabesmyia*	*PAG*	*Pagastiella*
BRYOP	*Byophaenocladius*	*PARAKb*	*Parakieferiella bathophila*- type
CHAEB	*Chaetocladius type B*	*PARAM*	*Paramerina*
CHIROa	*Chironomus anthracinus*- type	*PARAMET*	*Parametriocnemus*
CLADOm	*Cladotanytarsus mancus*- type	*POLYnu*	*Polypedilum nubifer*- type
CORYe	*Corynoneura edwardsi*- type	*PROCL*	*Procladius*
CRYPT	*Cryptochironomus*	*PARAT*	*Paratanytarsus*
DEMIC	*Demicryptochironomus*	*PSECTbi*	*Psectrocladius barbimanus*- type
DICRne	*Dicrotendipes nervosus*- type	*PSECTca*	*Psectrocladius calcaratus*- type
EUKIEc	*Eukiefferiella claripennis*- type	*PSECTse*	*Psectrocladius septentrionalis*- type
GLYPpa	*Glyptotendipes pallens*- type	*PSECTso*	*Psectrocladius sordidellus/psiloperus*- type
HET_TAN	*Heterotanytarsus*	*PSEUDOR*	*Pseudorthocladius*
HETERgr	*Heterotrissocladius grimshawi*- type	*PSEUDOS*	*Pseudosmittia*
HETERmd	*Heterotrissocladius marcidus*- type	*STICTr*	*Stictochironomus rosenschoeldi*- type
LIM\PAR	*Limnophyes/Paralimnophyes*	*TANYgr*	*Tanytarsus gracilentus*- type
MACRO	*Macropelopia*	*TANYm*	*Tanytarsus mendax* -type
MICROj	*Micropsectra junci-type*	*TANYp*	*Tanytarsus pallidicornis*- type
MICRp	*Microtendipes pedellus-type*	*TANYun*	*Tanytarsus* undiffrenciated

Figure 5.9 PCA bi-plot of common chironomid taxa.

5.7 CHIRONOMID COMMUNITY COMPOSITION – ^{210}PB-DATED PORTION OF THE CORE

Thorough examination of the dated portion of the chironomid stratigraphy was carried out to gauge the relative influences of historical human impacts and climate change on the chironomid community. Three zones were identified using ZONE programme version 1.4 (Juggins, 1992), although none of these were found to be statistically significant using BSTICK model (Bennett, 1996). Zones are titled D-1, D-2 and D-3 in order to differentiate the zones in the ^{210}Pb-dated portion of the core from the entire chironomid stratigraphy.

5.7.1 D-1 (AD 1868 – AD 1894)

The dominant grouping of chironomid taxa in zone D-1 are those associated with eutrophic conditions, comprising ~36% of the chironomid community (Figure 5.10). *Microtendipes pedellus*-type (12%), *Tanytarsus pallidicornis*-type (11%), *Corynoneura edwardsi*-type (5%) and Polypedilum *nubifer*-type (3%) are the most plentiful fauna in this group, while *Parakiefferiella bathophila*-type, *Micropsectra junci*-type and *Procladius* are evident in smaller numbers. In the Irish training set (Potito *et al.*, forthcoming), these taxa are associated with eutrophic lakes with prominent agricultural activities in the catchment. Taxa that thrive in acidic or bog lakes are the second dominant group in this zone, amounting to ~23% of the fauna. *Heterotanytarsus* (17%) is the most dominant fauna in this group and is associated with bog environments (Brook *et al*., 1997), with lower levels of *Psectrocladius sordidellus/psilopterus*-type (4%) and *Psectrocladius calcaratus*-type (2%) in this zone. Zone D-1 is characterised by the highest level of midge diversity (~4.9) and head capsule concentrations (23 head capsules ml^{-1}).

Taxa indicative of warm water conditions reach an average of 16%. *Pseudorthocladius* (5%), *Dicrotendipes pedellus*-type (5%), *Tanytarsus mendax*-type (4%) and *Cladotanytarsus mancus*-type (2%) comprise the majority of the group in this zone (Potito *et al*., forthcoming). Overall, these fauna display a slight decreasing trend throughout this zone. *Heterotrissocladius marcidus*-type (5%), *Heterotrissocladius grimshawi*-type (3.5%), *Stictochironomus rosenschoeldi*-type (2%) and *Psectrocladius septentrionalis*-type (1.5%) comprise the cooler, less productive fauna community, reaching levels of 12%. *Limnophyes/Paralimnophyes* (5%), *Parametriocnemus* (2%) and *Pseudsmittia* (2%) are also evident. These taxa are characteristic of littoral and/or semi-terrestrial environments, and are most abundant at the start of the zone.

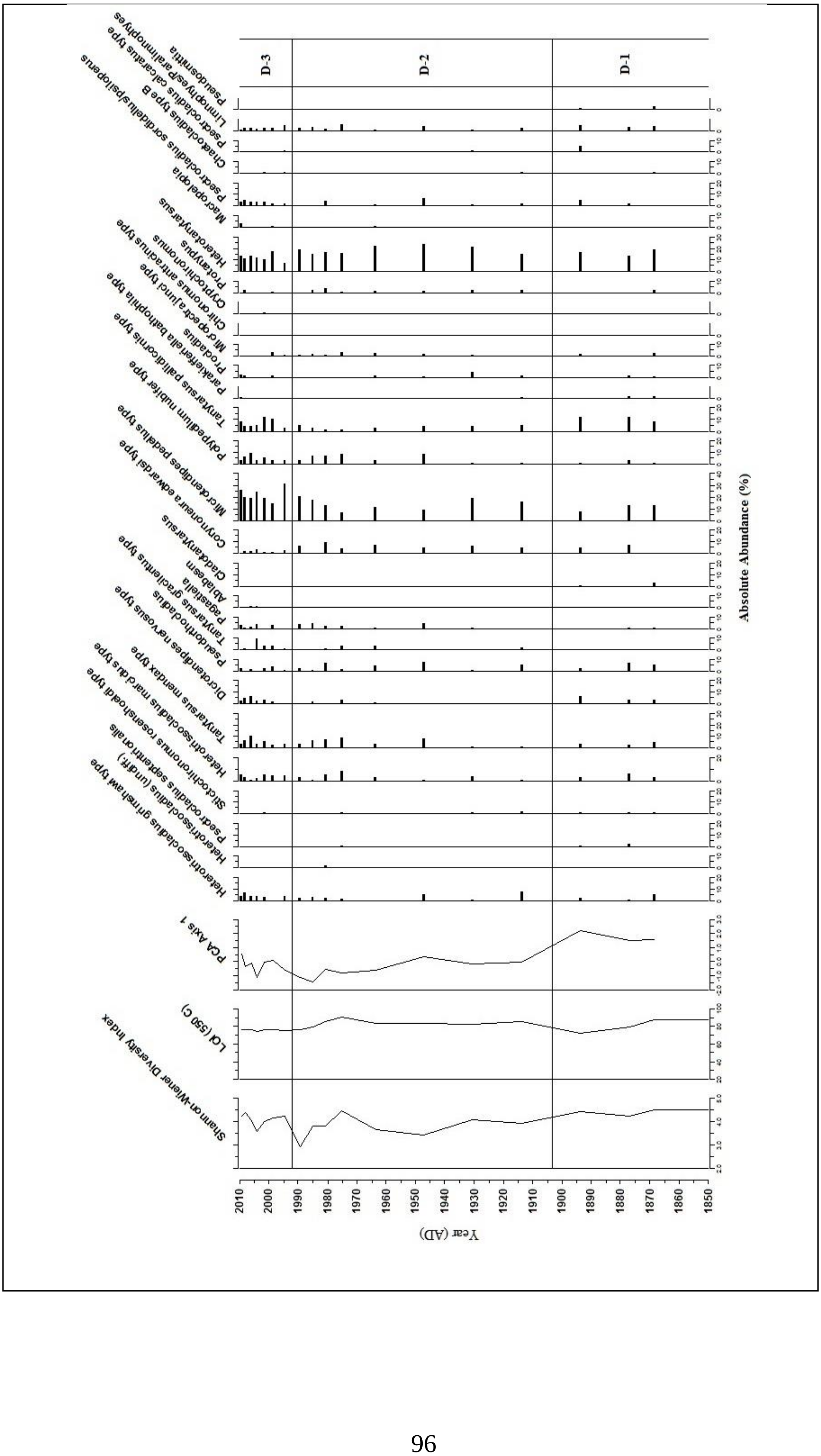


Figure 5.10 Chironomid stratigraphy for ^{210}Pb-dated section of the Lough Meenagraun sediment core.

5.7.2 D-2 (AD 1914 – AD 1990)

Fauna closely linked with eutrophic lake conditions remain prominent in this zone (35%). *Microtendipes pedellus*-type is the most dominant taxon of this group (15%), with greater numbers at the beginning of the zone. *Polypedilum nubifer*-type (6%), *Corynoneura edwardsi*-type (6%) and *Tanytarsus pallidicornis*-type (4%) are also prominent. *Corynoneura edwardsi*-type is stable at levels of around 6% until the mid-1960s. *Procladius*, *Parakiefferiella bathophila*-type and *Chironomus anthracinus*-type are also present but at notably lower levels. *Procladius* decreases throughout the first half of zone D-2 and is absent by the mid-1970s for the remainder of this zone. Taxa associated with acidic lake conditions make-up around 22% of chironomids in the zone. *Heterotanytarsus* (19%) is the most abundant fauna in this group. This taxon is associated with humic waters and becomes less abundant throughout the zone. *Psectrocladius sordidellus/psilopterus*-type remains at a low abundance, but shows a decreasing trend throughout the zone. Other taxa associated with acidophilic lake conditions, such as *Macropelopia*, *Eukiefferiella bathophila*-type and *Psectrocladius calcaratus*-type, are present in the first half of this zone before diminishing in the second portion.

Taxa associated with cooler, less productive lake conditions are at a relatively low abundance at the beginning of this zone. *Heterotrissocladius marcidus*-type remains at low levels at the onset of this zone before reaching levels of 9% in the mid-1970s, followed by a sharp decline to 1% in 1985. *Stictochironomus rosenshoeldi*-type decreases slowly in the first half of this zone before disappearing by the mid-1940s. On average, taxa linked with warmer waters show an overall increase throughout this zone levels of around 18%. *Pseudorthocladius* (5%), *Tanytarsus mendax* (2%) and *Tanytarsus gracilentus*-type (2%) are detected in the early portion of this zone, while *Dicrotendipes nervosus*-type and *Pagastiella* are absent at this time. *Cladotanytarsus mancus*-type and *Ablabesmyia* are not present at any stage in this zone. By the 1950s *Tanytarsus mendax*-type (9%), *Pseudorthocladius* (8%) and *Pagastiella* (5%) increase in abundance, while *Dicrotendipes nervosus*-type appears for the first time, albeit at 1%. *Tanytarsus mendax*-type (4%), *Pseudorthocladius* (5%) and *Pagastiella* (1.5%) all decrease in abundance by the mid-1960s. However, by the 1980s these thermophilic taxa increase in abundance and diversity. Taxa associated with terrestrial or semi-terrestrial environments, such as *Limnophyes/Paralimnophyes*

(3.5%), experience notable variability throughout this zone. In the Irish training set (Potito *et al.*, forthcoming) *Paratanytarsus* (2.5%) was associated with deeper water lakes. This taxon increases in abundance throughout this zone and may be indicative of increasing lake level. Finally, this zone is marked by the lowest level of diversity (according to the Shannon-Wiener Diversity Index) at ~3.8, and the lowest head capsule concentration with 19 head capsules ml^{-1} of wet sediment.

5.7.3 D-3 (AD 1994 – AD 2009)

Zone D-3 displays a further growth in taxa associated with eutrophic conditions, with an increase to around 41%. The main taxon responsible for this increase is *Microtendipes pedellus*-type (23%). *Tanytarsus pallidicornis*-type (7%), *Polypedilum nubifer*-type (5%) and *Corynoneura edwardsi*-type make-up most of the rest of this group, with low levels of *Micropsectra junci*-type, *Procladius* and *Parakiefferiella bathophila*-type. *Chironomus anthracinus*-type is absent from this zone. Warm water taxa also increase throughout this zone, comprising 17% of the chironomid community. *Tanytarsus mendax*-type and *Dicrotendipes pedellus*-type reach their highest levels around 2006. Both taxa show notable declines between 2006 and 2009. *Ablabesmyia* makes its only appearance in this zone in 2006. *Tanytarsus gracilentus*-type displays an increase in abundance from a level of 2% in 1995 to 10% in 2004, followed by a subsequent fall in abundance until it is absent in 2008. *Pseudorthocladius* and *Pagastiella* follow similar trends, with peaks in 1999, the mid-2000s and 2009.

The trend evident in these warmer taxa is mirrored in the taxa linked with cooler, less productive lake conditions. *Heterotrissocladius marcidus*-type reaches its lowest levels in 2006. *Stictochironomus rosenscholdi*-type displays a peak in numbers in 2002. *Heterotrissocladius grimshawi*-type reaches its lowest levels in 1999 and highest levels in 2008 and 2009. *Psectrocladius septentrionalis*-type is absent from this zone. These taxa, linked with cooler, less productive lake environments, make-up 8% of all taxa in this zone.

Heterotanytarsus, which is linked with the humic water of bog lakes, displays variability throughout the 1990s, fluctuating between around 8% and 18%. *Psectrocladius sordidellus/psilopterus*-type, which is an acidophilic taxon, increases throughout this zone. *Limnophyes/Paralimnophyes* displays a gradual declining trend over this zone. In addition, *Parametriocnemus* is only seen in this zone in 1994 and 2008. Both of these taxa are indicative of terrestrial/semi-terrestrial environments. Conversely, *Paratanytarsus*, which is indicative of deep water conditions, appears in 1999 and 2008. Finally, taxa diversity in this zone is 4.1 (Shannon-Wiener Diversity Index) and head capsule concentration averages at 21 head capsules ml^{-1}.

5.7.4. Community Compositional Change - ^{210}Pb-Dated Portion of Core

The transitions from zone 1 to zones 2 and 3 is evidence by a leftward shift in PCA Axis 1 (λ = 0.202) (Figure 5.11). Hereafter, conditions begin to shift towards the top of the bi-plot, across PCA Axis 2 (λ = 0.173). Samples in zone 1 comprise taxa associated with cooler waters and eutrophic lake conditions. These include *Stictochironomus rosenschoeldi*-type, *Psectrocladius septentrionalis*-type, *Tanytarsus pallidicornis*-type, *Paramerina* and *Pseudosmittia* (Figure 5.12). The shift from zone 1 to zone 2 along PCA Axis 1 can be explained by a transition towards warmer temperatures and more acidic lake conditions. Taxa such as *Heterotanytarsus* and *Tanytarsus mendax*-type are dominant on the left of the taxa bi-plot (Figure 5.12). The presence of taxa associated with eutrophic lake conditions such *Pagastiella*, *Polypedilum nubifer*-type and *Corynoneura edwardsi*-type indicated that the lake is still quite productive in zone 2.

The final shift from zone 2 to zone 3 is characterised by a shift across PCA Axis 2. This shift in trajectory can be explained by a shift towards warmer temperatures as there is an increase in *Tanytarsus mendax*-type and *Tanytarsus gracilentus*-type, associated with warmer lake conditions in the Ireland training set (Potito *et al*., forthcoming) (Figure 5.12). The samples at 1997 and 2005 are particularly indicative of warmer waters due to the dominance of *Tanytarsus mendax*-type. Furthermore, samples at 2009 and 2002 appear to be driven back to cooler conditions, as characterised by the re-emergence of *Heterotrissocladius grimshawi*-type and *Heterotrissocladius marcidus*-type in these samples.

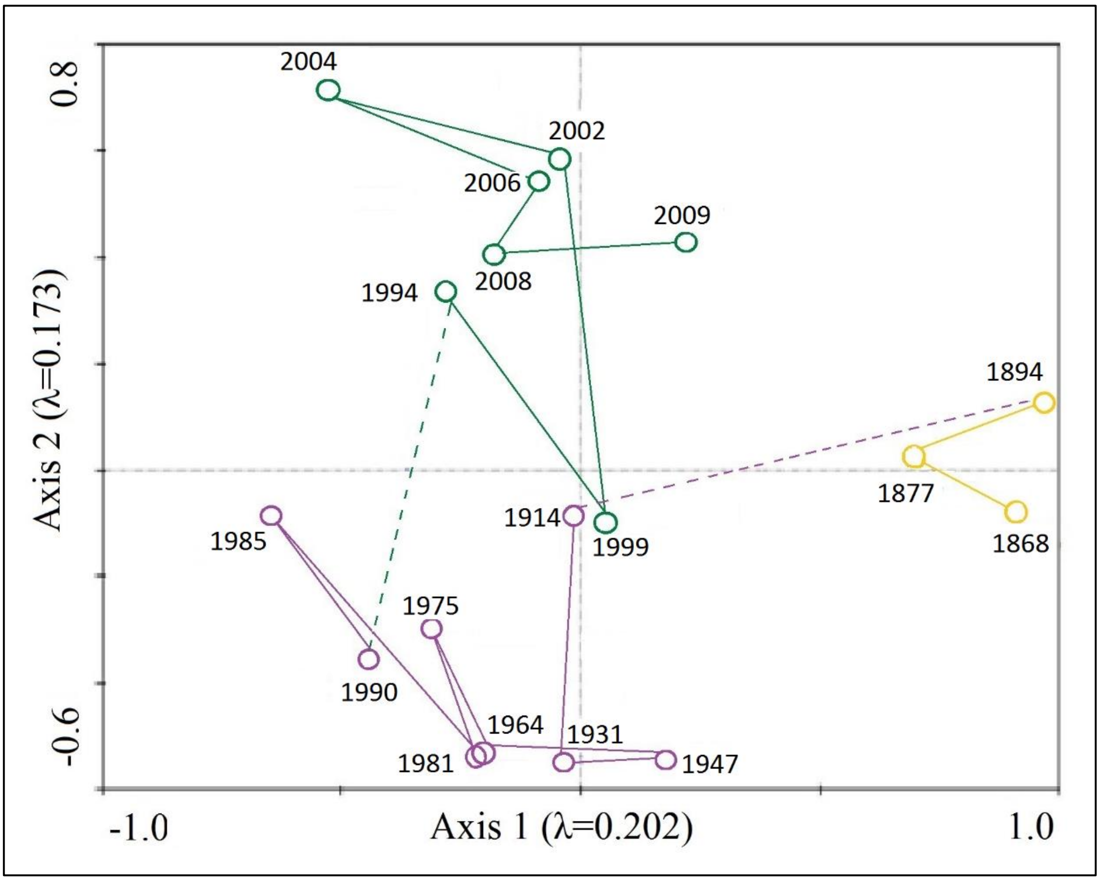


Figure 5.11 Time-trend principal component analysis (PCA) bi-plot chironomid samples displaying changes in chironomid trajectory over the ^{210}Pb-dated section of the core. Zones are highlighted in different colours.

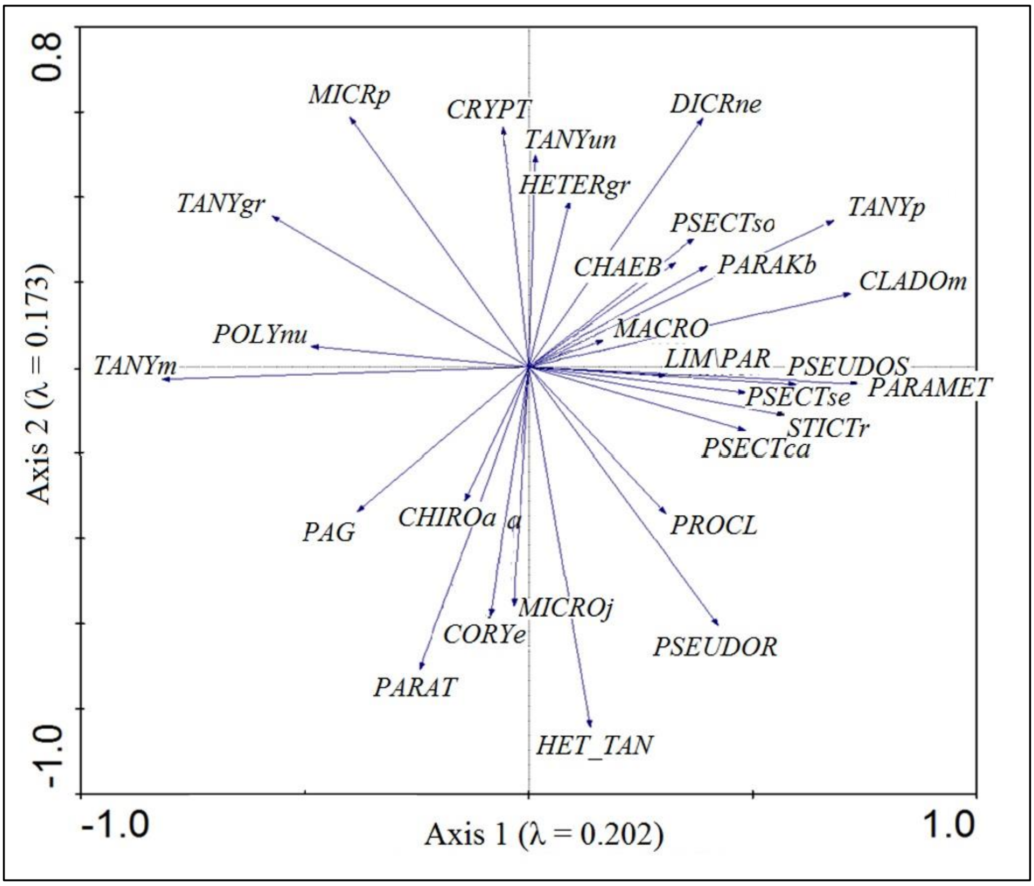


Figure 5.12 PCA bi-plot of common chironomid taxa from the ^{210}Pb-dated section of the sediment core. Taxa abbreviations follow those used in Figure 5.9.

5.8 CHIRONOMID-INFERRED TEMPERATURE RECONSTRUCTION

The chironomid-based temperature inference model (C-IT) for the dated portion of Lough Meenagraun is presented in Figure 5.13. C-IT ranged from 12.4°C to 13.2°C between 1868 and 2009. A general increase in temperature is observed throughout this model, with the warmest time periods occurring in the mid-1980s, late 1990s and mid-2000s. A LOESS smoother (span = 0.3) was applied to the reconstruction to highlight the main trends in air temperature over the ^{210}Pb-dated interval of the record. The smoothed data shows that air temperature was lower in the late 19th century and temperatures fluctuated throughout the 20th century, with a notable increase in temperature from the mid-1990s to 2006 (rate of warming of 2°C/100 yrs). A subsequent cooling trend between 2008 and 2009 has essentially altered the rate of warming from 1994 to 2009 to 0.5°C/100 yrs.

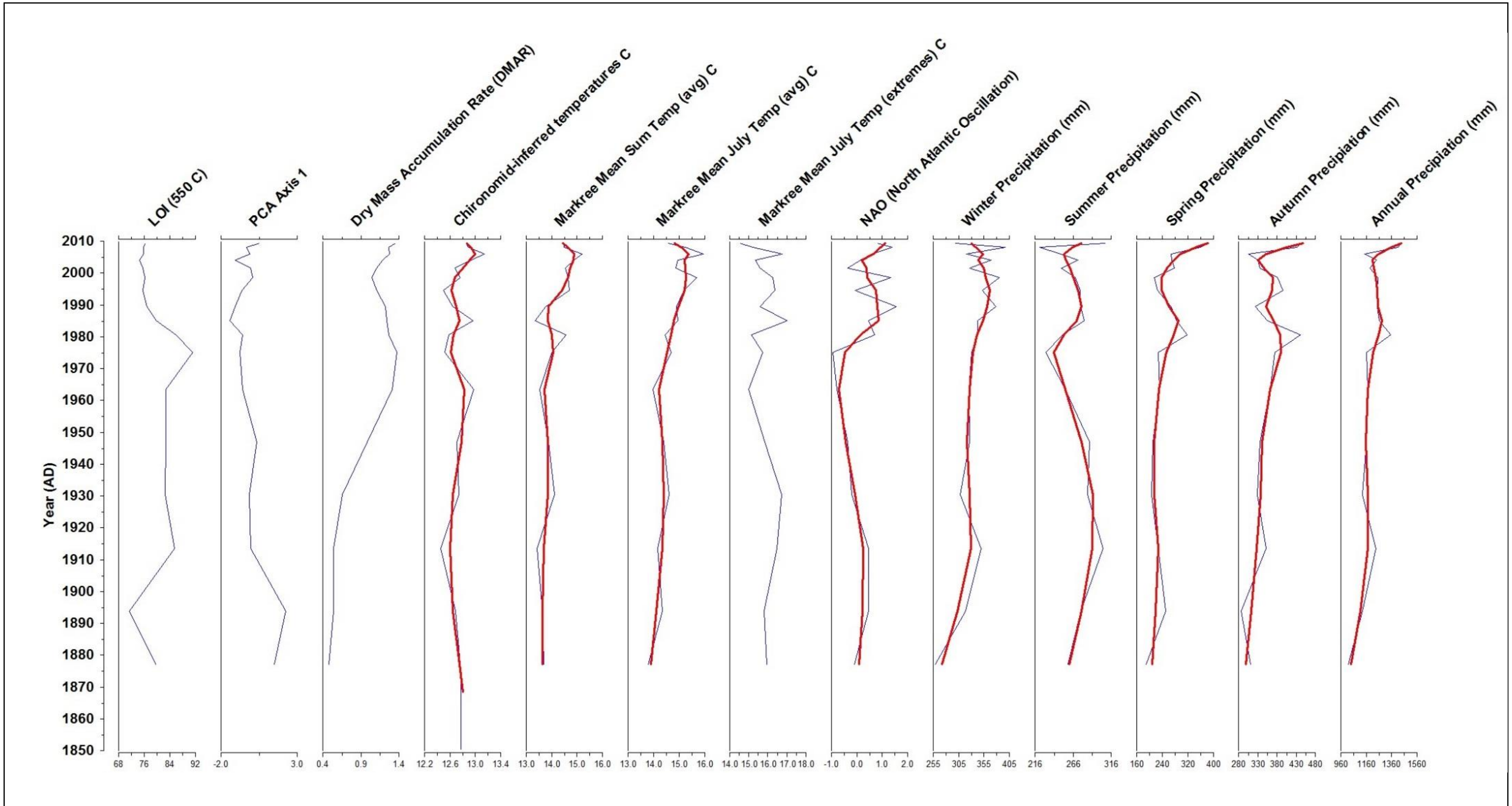


Figure 5.13 Chironomid-based summer air temperature reconstruction, chironomid PCA, LOI, DMAR, of Lough Meenagraun and Markree summer temperature, seasonal precipitation and NAO index (red lines indicate LOESS smoother with a span of 0.3).

To assess the sensitivity of chironomid community to long term temperature and precipitation change, data from Markree Observatory was compared to limnological information. This climate station is the closest long-term monitoring station (pre-1960) to Lough Meenagraun. Local temperature differences between the two locations were assessed using air temperature data loggers and accepted lapse rates, and despite differences in elevation, rates of daily temperature change at the both sites are largely synchronous. Markree temperature and precipitation data were adjusted to match the resolution of the lake data. Each 0.5 cm section of the lake sediment represents between one and six years of sedimentation after 1975. From 1877 to 1975, each 0.5 cm section of the sediment core represents a much broader time span of 16 to 22.5 years. Summer air temperature and seasonal precipitation data were also averaged over each sediment interval in order to represent climate conditions during that interval.

C-IT were subsequently compared to the Markree mean summer (June, July and August), and Markree mean July temperature records. The inferred temperatures were also compared to a dataset whereby the warmest average July temperatures for each sample interval were extracted. This was carried out in order to gain a comprehensive understanding of the response of chironomids to recent warming trends. A LOESS smoother (span = 0.30) was applied to the Markree mean summer and July temperature records to highlight main trends in the data. This was not applied to the record containing the warmest July years for each time interval, as this curve was constructed to capture the extremes. All chironomid-inferred temperature records display lower values in the late 19th century in line with the Markree mean summer, mean July and warmest July records. The chironomid-temperature model appears to be following the mean July temperature record more closely than the mean summer temperature record over the entire 20th century. The falling temperatures in the mid-1970s to early-1980s evident in the Markree mean summer temperature record are not observed in the mean July temperature record, warmest July average temperatures or the chironomid-inferred temperature reconstruction. Temperature change in the early-21st century is similar in all records, where temperatures increase to 2006, before falling to 2009. Furthermore, the inferred warmest years in the July record explain the high values seen in the chironomid-inferred temperature reconstruction in the mid-1980s, the 1990s and mid-2000s. This highlights the complexity of the chironomid response to summer air temperature, indicating that years with July heat waves seem to have a notable impact on the chironomid community.

The chironomid-temperature reconstruction was then extended beyond the scope of the ^{210}Pb-dated section of the core (Figure 5.14), in order to establish longer temperature trends in the more distant past. As ^{14}C-dating was deemed inaccurate, the sediment layers beyond the ^{210}Pb-dating model cannot be confidently linked with calendar years. However, anecdotal links can be made between C-ITs and points in time through extending the dry mass accumulation rate from the bottom-most portion of the ^{210}Pb-dating model through the rest of the core.

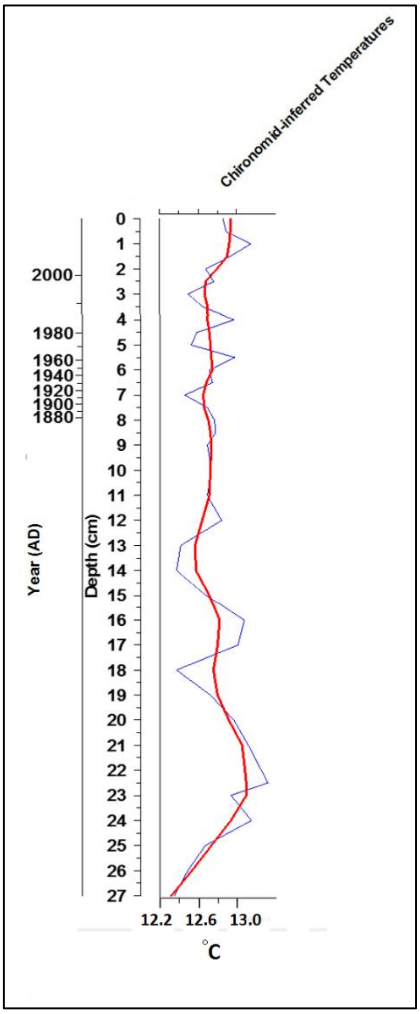


Figure 5.14 Chironomid-inferred temperature reconstruction over the full Lough Meenagraun sediment core.

Taking the C-ITs spanning ~1850 to 2009 as baseline climate conditions (the mean over this time period is 12.8°C), temperatures remain relatively constant between 9 cm and 11 cm (estimated here as 1835 to 1770) with a mean of 12.6°C. A preceding cooler period is evident between 12 cm and 14 cm (estimated as 1730 to 1665), where temperatures fall to 12.3°C by ca. 1665. Prior to this cool period, a warmer phase is evident between 14 cm and 17 cm (estimated as 1630 and 1560), where temperature increases to 13°C by ca. 1560. A sharp cooling period predates this warm phase, where temperatures were ~12.4°C by 18cm (ca. 1530). C-ITs show the warmest conditions at 24 cm (ca. 1325), reaching an average of 13.2°C. Finally, cooler C-ITs are evident between 25 cm and 27 cm (estimated as 1290 to 1220). It must be noted that the temperatures over these depths are rising from 1220 to 1290, indicating a movement from cooler into warmer conditions.

5.9 CLIMATE AND LAKE VARIABLES THROUGH TIME

To assess the sensitivity of chironomids to recent environmental change PCA Axis 1 scores, organic carbon (550°C) and dry mass accumulation rates (DMAR) were examined along with Markree seasonal and annual precipitation and winter North Atlantic Oscillation (NAO) index values (Figure 5.13). This was carried out to explore the dominant climate/environmental controls on the chironomid community through time. The NAO index values, which have the strongest influence on winter climate, have been shown to have an influence on precipitation patterns, which could in turn, have a discernible impact on biological activity within lakes (Livingstone *et al*., 2010; Jennings *et al*., 2000). All environmental and climate records were adjusted to match the resolution of the lake data. This allows the PCA values and C-IT model to be compared to the Markree climate records and NAO index values across the same time intervals. When compared, PCA Axis 1 scores and NAO index values do not follow any notable trend, nor do NAO index values and the chironomid-inferred temperature data. Furthermore, no synchronous patterns were evident between precipitation values and trends in chironomid PCA Axis 1, LOI (550˚C) and DMAR. Interestingly, organic carbon appears to be following chironomid PCA Axis 1 scores in the earliest portion of the stratigraphy from the late 19th century until the mid-1950s, indicating that organic carbon is likely influencing the chironomid community in this section of the core.

5.10 REDUNDANCY ANALYSIS (RDA)

To provide a deeper exploration of the relationship between chironomid community change and climate variables, redundancy analysis (RDA) was carried out on all samples since 1880. The five variables selected were summer temperature, LOI 550°C (organic carbon), winter precipitation, spring precipitation and summer precipitation. NAO was excluded in the redundancy analysis as this phenomenon is a combination of numerous climate variables, and is a driver of seasonal temperature and precipitation rather than a local influence. DMAR was also not included, as more than half of the DMAR values (samples between the dated layers) are interpolated. Finally, autumn precipitation was excluded as there is no hypothesis-driven reason for its inclusion. The five variables chosen explain 36.5% of the chironomid community variance, with RDA Axis 1 explaining 13.3% and RDA Axis 2 explaining 11% (Table 5.1).

Table 5.1 Redundancy analysis (RDA) utilised linear responses showing eigenvalues species environmental correlations, cumulative percentage variance in species data, canonical coefficients and T-tests.

	Axis 1	Axis 2	Axis 3	Axis 4
Full model				
Eigenvalue	0.133	0.110	0.080	0.420
Species-envt. Corr.	0.860	0.848	0.814	0.730
Cum.% var. Spp.	13.3	24.3	32.3	36.5
Canonical coefficients				
Summer air temp	-0.521	-0.409	-0.163	0.034
LOI	0.772	-0.137	-0.009	0.282
Winter precipitation	-0.015	-0.631	0.027	-0.470
Spring precipitation	-0.436	-0.482	-0.038	0.305
Summer precipitation	-0.074	0.216	0.780	0.055
Significant T-values				
Summer air temp	-2.363*	-1.737	-0.639	0.134
LOI	4.711**	-0.538	-0.035*	1.139
Winter precipitation	-0.05*	-3.154**	0.104	-2.066
Spring precipitation	-1.878	-2.134*	-0.148	1.24
Summer precipitation	-0.29	0.859	-0.639	0.213

**P < 0.01, *P < 0.05
Species-envt. Corr. = species environment correlation for each axis
Cum.% var. Spp. = cumulative percent variance in species data

LOI (550°C) and summer temperature show the strongest relationship with Axis 1, while winter and spring precipitation show their strongest relationship with Axis 2 (Table 5.1). The RDA bi-plots (Figure 5.15 and Figure 5.16) capture the degree of variance that LOI (550°C) and summer temperature have on the chironomid data through time. A temperature gradient is captured in the RDA species-environment bi-plot. Samples with a high percentage of cold water taxa such as *Psectrocladius septentrionalis*-type and *Stictochironomus rosenschoeldi*-type are grouped in the upper right quadrant of the sample-environmental bi-plot (Figure 5.16) and have a negative relationship with summer temperature. These samples span the late 19th century until the mid-1980s, indicating cooler conditions at this time, while samples from 1985 to 2009 contain lower percentages of these cooler water taxa, in turn indicating warmer conditions in recent years. The RDA sample-environmental bi-plot shows that samples post-1985 are positively related to summer temperature.

The species-environmental bi-plot also shows that *Heterotanytarsus,* which is associated with humic waters, is closely related to LOI (550°C) (Figure 5.15). This taxon is found in their highest abundance in the pre-1985 samples and are clustered in the right hand side of the sample-environment bi-plot (Figure 5.16). The ordination diagram separates out the samples through time, with samples before 1985 containing a higher levels of this taxon indicating that the lake likely had a greater humic water conditions at this time. Samples between 1985 and 2009 contain lower levels of *Heterotanytarsus*, this signifies a reduction is humic water conditions. A synchronous and notable abrupt decline in organic carbon content (see Figure 5.3) and the dry mass accumulation rate (see Figure 5.4) occurred in 1980s, followed by a subsequent stabilisation in values up to 2009. This likely indicates that a reduction in the input of terrestrial peat material to the lake occurred after 1985, likely the result of decreased land disturbance from sheep grazing. As *Heterotanytarsus* thrives in humic waters, a decline in such conditions will reduce the population of this taxon. Therefore, a reduction in the intensity of human activities in the catchment at a time when warming conditions began to establish allowed summer temperature to be the strongest variable influencing the chironomid trajectory post-1985.

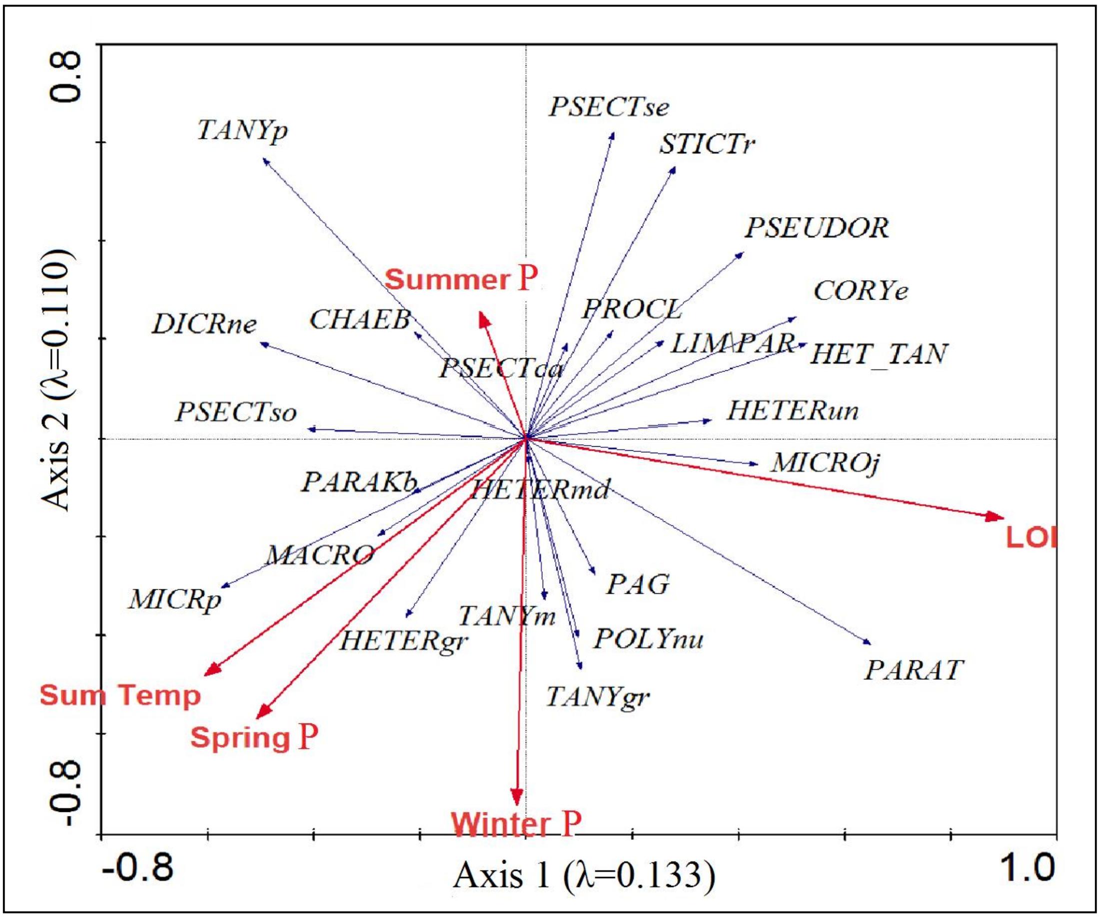


Figure 5.15 RDA bi-plot showing species distribution being influenced by LOI, summer temperature (Sum Temp), winter precipitation (Winter P), spring precipitation (Spring P), summer precipitation (Sum P).

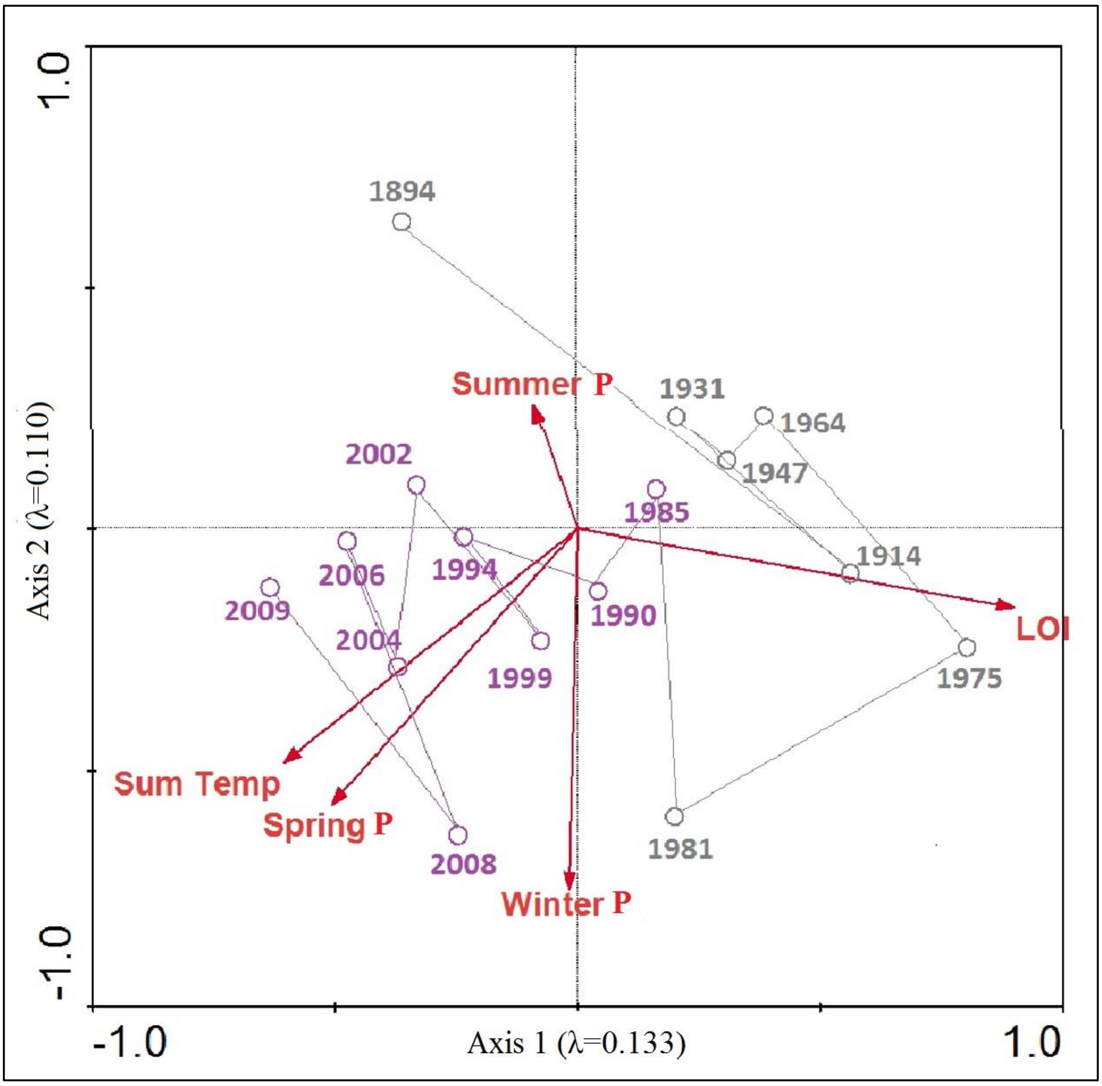


Figure 5.16 RDA bi-plot showing sample distribution being influenced by LOI, summer temperature (Sum Temp), winter precipitation (Winter P), spring precipitation (Spring P), summer precipitation (Sum P).

Partial RDAs illustrate that LOI and summer temperature are having the greatest influence on chironomid community change, explaining 11.6% and 8.4% of variance, respectively (Table 5.2). These variables displayed $\lambda 1/\lambda 2$ ratios of 0.477 for summer temperature and 0.895 for LOI (Table 5.2). LOI became stronger once seasonal precipitation was factored out (14.4%), while spring rainfall increased slightly (8.6%) once winter and summer precipitation were partialled out. Both winter and summer precipitation became stronger when all other variables were partialled out (10.7% and 11.3% respectively). Summer temperature weakens slightly when any combination of variables is factored out. Although P-values illustrate that summer temperature is not significant, it seems to have an influence on chironomid community over the recent past, especially after mid-1980s, when samples steadily follow an increasing temperature trend.

Table 5.2 Partial RDA for each environmental variable.

Variable	Covariable	λ1	λ1/λ2	P	% variance
Summer Air Temperature	None	0.084	0.477	0.138	8.4
	LOI	0.63	0.44	0.38	7.2
	Seasonal precipitation	0.055	0.341	0.554	7.2
	LOI, seasonal precipitation	0.04	0.35	0.756	6.1
LOI	None	0.116	0.67	0.014	11.6
	Sum temperature	0.096	0.671	0.052	10.5
	Seasonal precipitation	0.111	0.895	0.012	14.4
	Summer temperature, seasonal precipitation	0.096	0.842	0.03	13.5
Winter Precipitation	None	0.079	0.401	0.18	7.9
	Summer temperature	0.07	0.426	0.28	7.7
	LOI	0.085	0.578	0.072	9.6
	Spring and summer precipitation	0.069	0.377	0.308	8.3
	Summer temperature, LOI, spring and summer precipitation	0.074	0.679	0.194	10.7
Spring Precipitation	None	0.082	0.443	0.178	8.2
	Summer temperature	0.053	0.3011	0.658	5.8
	LOI	0.071	0.476	0.26	8.1
	Winter and summer precipitation	0.072	0.393	0.284	8.6
	Summer temperature, LOI, winter and summer precipitation	0.049	0.429	0.624	7.4
Summer Precipitation	None	0.082	0.414	0.136	8.2
	Summer temperature	0.083	0.482	0.116	9
	LOI	0.081	0.487	0.088	9.2
	Winter and summer precipitation	0.08	0.437	0.124	9.5
	Summer temperature, LOI, winter and spring precipitation	0.078	0.684	0.11	11.3

P = significance level of Monte Carlo permutation tests (499 unrestricted permutations.

5.11 SYNOPSIS

There is an obvious regime shift in the Lough Meenagraun chironomid community in the mid-19th century. Suding and Hobbs (2009) integrated threshold theory in ecological models to human-impacted systems and showed that human activities can introduce new threshold triggers that can shift an ecosystem to an alternative stable state. The introduction or expansion of agricultural activities around the lake catchment in the mid-19th century likely altered the capacity of the system to cope with the environmental change, and shifted the chironomid community to an alternative stable state. Scheffer *et al*. (1993) and Hobbs *et al*. (2012) provides evidence for the ability of shallow lake systems to stay relatively stable in an alternative state once a regime shift takes place.

Eutrophic taxa associated with agricultural activity such as *Tanytarsus pallidicornis*-type, *Microtendipes pedellus*-type, *Procladius* and *Polypedilum nubifer*-type dominate the most modern section of the core in zone 2 (Figure 5.7). Evidence extracted from historical land-use records indicate that sheep farming increased in the area after 1850. This change in taxa assemblage around the 1850s corresponds with a shift in agricultural activity which took place in the Glenade area. On a national scale, a shift in agricultural practice took place in Ireland after the Great Irish Famine of 1845 to 1849. Agricultural output in the early to mid-19th century was mainly in the form of arable farming. Ó Danachair (1970) states that between 1780 and 1840 the area of land used for crop cultivation in Ireland was larger than ever before. Post-famine times (post-1850) marked a shift from arable farming to pastoral activity. Animal husbandry now made use of upland areas that were not conducive to arable practices. Another feature of the Famine was the marked decline in the national population of Ireland. The majority of urban and rural areas suffered vast population declines post-1850 as a result of starvation, disease and emigration brought about by famine conditions. Evidence from population dynamics at Electoral District level shows an unusual trend of population increase in the Glenade area in the late 19th century, which is not evident in surrounding districts. The population increase in the Glenade region is unique and indicates that people were likely moving into this area from the surrounding districts. In addition, remains of a formerly-active sheep fold indicate that sheep were enclosed around Lough Meenagraun. Such a feature was likely erected around the time when a shift in agriculture took place in the surrounding area.

The shift in catchment land only accounts for part of the alteration in midge community structure. Evidence from the chironomid stratigraphy further indicates that an event took place around the lake ca. 1850. In the chironomid stratigraphy, the presence of taxa associated with terrestrial/semi-terrestrial environments, such as *Bryophaenocladius* and *Smittia,* indicate a potential erosion event. At this time the number of *Cladotanytarsus mancus*-type falls substantially. This taxa is associated with the presence of coarse sediments on submerged banks (Luoto *et al*., 2008), and can be indicative of erosion processes, aeolian deposits or local input from streams. The taxa decreases in abundance in the mid- to late 19th century and is absent for the 20th century. Furthermore, increasing levels of *Paratanytarsus* (indicative of deep water environments), *Limnophyes/Paralimnophyes* and *Pseudosmittia* (both indicative of terrestrial/semi-terrestrial environments) post-1850 suggest that the level of the lake could have increased.

Examining contemporary morphology of the lake, the presence of boulders around the output stream indicates that the outflow was likely dammed, in turn flooding surrounding shelves comprised of humic material. The lake is likely to have been dammed in conjunction with the intensification of sheep farming around the catchment. Taxa which thrive in acidic/humic environments become more dominant post-1850, notably *Heterotanytarsus*. This bog taxon is associated with the littoral of humic (brown water) lakes (Brudin, 1945; Saether, 1979; Cranston, 1982). *Limnophyes/Paralimnophyes*, *Heterotanytarsus* and *Paratanytarsus* are associated with high organic carbon, as shown in the RDA species-environmental bi-plot. This signifies that organic carbon is likely associated with changes in lake level, which may have occurred as a result of human activity at this site since 1850. The expansion in the numbers of taxa associated with eutrophic and productive lake conditions after 1850, as identified in the Irish training set (Potito *et al*., forthcoming), further supports the assumption of increased pastoral activity within the lake catchment.

Despite the large-scale human impact around the catchment of Lough Meenagraun and the strong relationship between LOI and the chironomid community as evidenced from RDA, a temperature signal still emerges from the chironomid data. Temperature changes over the length of the Markree summer and July temperature records closely track changes in the chironomid-temperature reconstruction over the late 19th to early 21st century. The RDA samples bi-plot shows that temperature seems to become more influential by the mid-1980s. This marks the period when summer warming became prominent in instrumental records. The results from Lough Meenagraun further clarify the sensitivity of midges to subtle, but still evident, temperature change. In addition, the complexity of chironomid response to summer temperature was identified. Here, mean July temperatures and anomalously-warm years in the month of July (taking the warmest July month over the sample interval) followed the chironomid-temperature inferences model more closely than Markree mean summer temperatures (taking the average from each sample's interval).

The chironomid-temperature reconstruction was further extended beyond the scope of the ^{210}Pb-dated section of the core using dry mass accumulation rate to infer dates at all sediment depths (Figure 5.14). Taking the chironomid-inferred temperatures spanning ~1850 to 2009 as baseline climate conditions (average over this time period is 12.8°C) and working backwards through time, a colder period is evident between 1650 and 1730 (average of 12.3°C). This cooler period could potentially be the known period of colder temperatures known as the Little Ice Age in Europe. The period is estimated to have begun ~1500 and persisted until ~1850 (Turney *et al*., 2006; McDermott *et al*., 2001; Lamb *et al*., 1984). Predating this period was the Medieval Warm Period, a known climatic optimum which lasted from ~950 until ~1500 (Turney *et al*., 2006; McDermott *et al.*, 2001). This period is suspected to have had warmer temperatures than those experienced today. In the chironomid-temperature reconstruction, higher temperatures were inferred between 1325 and 1560 where C-IT were estimated to reach 13.1°C by 1560, which may correspond to this climatic period. At the bottom of the Lough Meenagraun core, cooler temperatures are evident between 1290 and 1220, where C-ITs where estimated to be 12.5°C. This period could be the end of the period known as the Dark Ages, which is thought to have taken place between 250 and 1000 (Turney *et al*., 2006). It must be noted that all inferred dates below the ^{210}Pb-dated portion of the core are based solely on estimated sedimentation rates and should only be regarded as an exploration of potential temperature patterns. However, broad trends in the data do seem to agree with known events as the Little Ice Age and Medieval Warm Period.

CHAPTER 6: LOUGH BALLYGAWLEY

6.1 LAND-USE HISTORY

Lough Ballygawley has a rich history of human interaction within its catchment. Lake drainage, agricultural activity and forest management are the primary activities that have taken place at this site since the mid-19th century. Information contained in historical documents dating to the 1880s provides evidence for large-scale planting of forestry in Union Wood. O'Rourke (1889) states that between ~1860 and ~1890, Colonel Cooper actively planted *Betula pendula, Quercus robur* and *Fagus sylvatica* in this area, which was part of the Markree Demesne at this time. Fieldwork surveys carried out by Coillte since the 1980s (Table 6.1) show that forestry was later expanded on the eastern sections of the land bordering the lake in Areas 1, 2, 3, 4 and 5 (Figure 6.1). This expansion took place in 1948 and 1949, and again between 1961 and 1964, before continuous management from the 1980s to present. *Picea abies, Abies procera*, *Picea sitchensis, Pinus sylvestris, Pseudotsuga menziesii* and *Larix kaempferi* were the main species planted over these time periods (Table 6.1).

Table 6.1 Areas of forestation and deforestation, species type, plant years, fell years and harvest years.

Area	Sub-areas	Area (ha)	Survey Year	Species	Canopy %	Plant Year	Thin Year	Fell Year
1	1a	5.9	1998	Douglas Fir	61	1964	1983	2008
				Spruce	11	1964		
				Scots Pine	16	1949		
				Norway Spruce	13	1961		
	1b	6.5	1998	Douglas Fir	36	1964	1989	2028
				Spruce	46	1964		
				Scots Pine	18	1949		
	1c	1.5	2007	Sitka Spruce	85	2002	2022	2042
				Beech	8	1949		
				Larsons Cypress	2	2002		
				Scots Pine	2	1949		
	1d	1.2	1998	Douglas Fir	62	1964	1989	2028
				Sitka Spruce	38	1964		
	1e	0.8	1998	Douglas Fir	78	1962	1981	2018
				Norway Spruce	22	1962		
	1f	1.7	1998	Noble Fir	65	1961	1986	2029
				Douglas Fir	35	1961		
	1g	1	1997	Oak	60	1900	1928	2009
				Spruce	40	1964		
	1h	2.6	1998	Sitka Spruce	80	1964	1982	2002
				Norway Spruce	20	1964		
2	2a	4.7	2001	Scots Pine	52	1948	1971	2017
				Norway Spruce	48	1948		
	2b	2.4	2001	0	0	0	0	0
	2c	0.5	2001	Sitka Spruce	100	1976	1995	2015
	2d	1.9	2001	Scots Pine	100	1948	1974	2019
	2e	0.6	2001	Sitka Spruce	100	1949	1969	1989
	2f	3.3	2002	Sitka Spruce	80	1997	2017	2037
				Japanese Larch	10	1996		
				Other Boradleaves	10	1997		
	2g	0.5	1996	Sitka Spruce	100	1990	2010	2030
	2h	1.3	2000	Japanese Larch	90	1997	2015	2042
				Sitka Spruce	10	1997		
3	3a	3.8	1981	Lodgepole pine	100	1948	1992	2028
	3b	2.5	2002	Sitka Spruce	100	1997	2018	2039
	3c	1.2	1981	Scots Pine	100	1948	1982	2039
	3d	2.9	2007	Sitka Spruce	50	2005	2032	2055
				Lodgepole pine	50	2005		
	3e	1.1	1981	Scots Pine	100	1948	1974	2019
	3f	1.2	1981	Scots Pine	100	1948	1974	2012
	3g	0.6	1981	Scots Pine	100	1948	1974	2019
	3h	1.8	1997	Oak	50	1890	1918	0
				Spruce	50	1964	n/a	0
	3i	2.1	1986	Scots Pine	85	1947	1977	2013
	3j	2	2007	Sitka Spruce	80	2003	2027	2049
				Beech	10	1947	2027	2049
				Other conifers	5	1947	2027	2049
				Other broadleaves	5	1947	2027	2049
	3k	1.1	1996	0	0	0	0	0
4	4a	4.4	1999	n/a	Felled	n/a	n/a	n/a
	4b	1.1	1981	Other broadleaves	50	n/a	n/a	n/a
				Birch	50	n/a	n/a	n/a
	4c	2	1981	Noble Spruce	100	1949	1971	1996

Area	Sub-areas	Area (ha)	Survey Year	Species	Canopy %	Plant Year	Thin Year	Fell Year
5	5a	6.2	2000	Beech	85	1947	1984	n/a
				Oak	15	1947	1984	n/a
	5b	2.3	2001	Sitka Spruce	80	1996	2016	2036
				Japanese Larch	20	1996	2016	2036
	5c	0.7	2007	Birch	81	2003	n/a	n/a
				Beech	10	1947	n/a	n/a
				Oak	3	1947	n/a	n/a
				Highbred Larch	1	2003	n/a	n/a
	5d	2.5	2007	Highbred Larch	60	2003	2022	2048
				Oak	20	1947	2022	2048
				Beech	10	1947	2022	2048
				Sitka Spruce	10	2003	2022	2048
	5e	4.9	2007	Beech	55	1947	n/a	n/a
				Sitka Spruce	40	2003	n/a	n/a
				Oak	5	1947	n/a	n/a
	5f	1.9	2007	Sitka Spruce	98	2003	2024	2045
				Beech	2	1947	2024	2045
	5g	0.9	2001	Sitka Spruce	90	1995	2015	2035
				Japanese Larch	10	1995	2015	2035
6	6a	21.8	2004	Sitka Spruce	81	2004	2025	2046
				Alder	11	2004	2025	2046
				Birch	5	2004	2025	2046
				Japanese Larch	3	2004	2025	2046
	6b	2.4	1981	Birch	60	n/a	n/a	n/a
				Other Broadleaves	40	n/a	n/a	n/a
	6c	0.8	1981	Scots Pine	100	1949	1975	2046
	6d	0.3	1987	Swamp				
	6e	1.1	1996	Sitka Spruce	100	1990	2009	2029
	6f	1.1	1996	Sitka Spruce	100	1992	2012	2032
7	7a	7.3	2005	Noble Spruce	95	2005	2030	2054
				Birch	5	2005	2030	2054
	7b	4.9	2005	Birch	50	n/a	n/a	n/a
				Other broadleaves	50	n/a	n/a	n/a
	7c	1.9	2005	Noble Spruce	95	2005	2030	2054
				Birch	5	2005	2030	2054
	7d	1.3	1997	Sitka Spruce	100	1994	2014	2034
8	8a	2.1	1997	Sitka Spruce	100	1994	2014	2034
	8b	7.8	2001	Sitka Spruce	95	1997	2016	2036
				Oak	5	1997	2016	2036
	8c	4.7	2001	Japanese Larse	70	1997	2013	2040
				Sitka Spruce	30	1997	2013	2040
	8d	2.2	2001	Sitka Spruce	85	1997	2016	2036
				Oak	15	1997	2016	2036
	8e	1.4	2009	Sitka Spruce	97	1990	2008	2028
				Birch	2	1990	2008	2028
	8f	1.6	2001	Sitka Spruce	100	1997	2016	2036
9	9 a	1.5	2001	Sitka Spruce	100	1997	2016	2036
	b	0.8	2001	Japanese Larse	15	1997	2013	2040
				Sitka Spruce	85	1997	2013	2040
	c	1.1	1997	Sitka Spruce	100	1994	2014	2034
	d	7.6	2001	Sitka Spruce	85	1990	2008	2028
				Birch	15	1990	2008	2028
	e	7.3	2001	Noble Spruce	50	1990	2008	2028
				Birch	50	1990	2008	2028
	f	2.1	1981	Birch	60	n/a	n/a	n/a
				Other Broadleaves	40	n/a	n/a	n/a

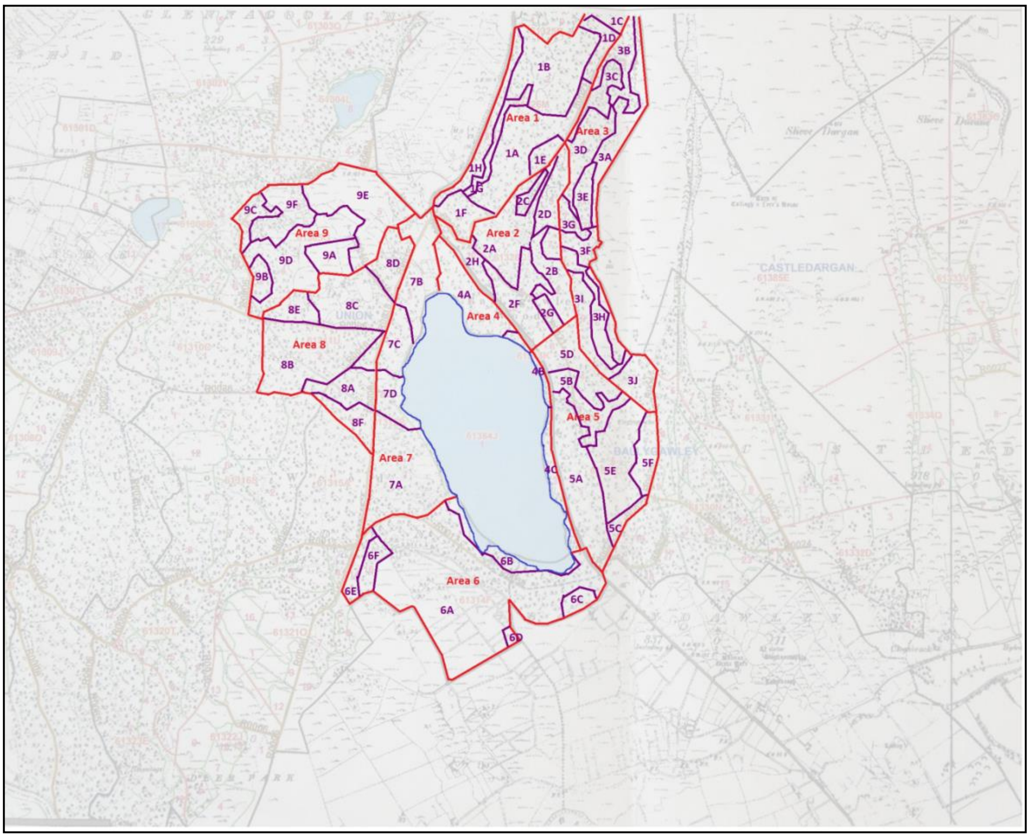


Figure 6.1 Zones of forestation and deforestation. Modified from Coillte Forestry Plan (2011).

There is also evidence of *Quercus robur* being planted in 1900 (Table 6.1). To the west of Lough Ballygawley, in Areas 6, 7, 8 and 9 (Figure 6.1), the majority of planting took place over the 1990s to the mid-2000s. Only a small number of *Pinus sylvestris* were planted in 1949 in Area 6, sub-section C (Figure 6.1, Table 6.1). Evidence contained in 25” maps (25 inches to one mile) created in 1907 as part of the Griffiths Land Evaluation (Ordinance Survey Ireland) displays the areas of land covered with forestry planted by Colonel Cooper the owner of Markree Castle (Figure 6.2a). Further evidence in orthographic photographs from the 2000 and 2005 (Figure 6.2b and Figure 6.2c) demonstrates the intensity of recent forest management (osi.ie), with large sections of Areas 6 and 7 showing forest clearance between these years. Forest expansion has occurred in all other areas around the lake between 2000 and 2005.

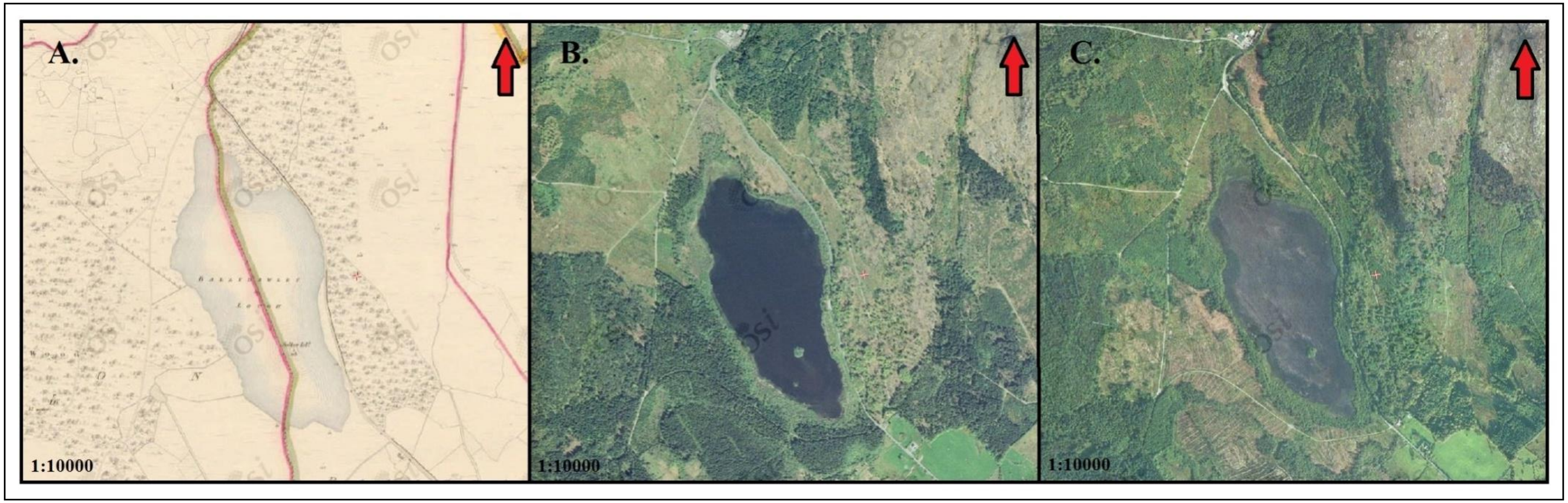


Figure 6.2 Hand-drawn and orthophotographic maps of Lough Ballygawley from Ordnance Survey Ireland. A) = 25” map created in 1907 as part of Griffiths Land Evaluation. B) = Orthophotograph taken in 2000 (osi.ie). C) = Orthophotograph taken in 2005 (osi.ie).

The orthographic photograph dating to 2005 (Figure 6.2c) shows the existence of arable cultivation ridges, commonly called ‘lazy beds’. The practice of building up-ridges on strips of untilled land has been regarded by agriculturalists as being particularly associated with Ireland in the 19th century (Bell, 1984). This provides visual evidence for the existence of agricultural activity around the lake in the 19th century. The extinction of *Lobelia,* likely as a result of run-off entering this lake, provides evidence of more recent agricultural activity (Dougles, 1992). The maps and photographs of this lake over the last 100 years provide further visual evidence for the drainage of the lake. The lake water covers a greater surface area in the beginning of the 20th century (Figure 6.2a) when compared to the modern orthographic photographs in 2000 (Figure 6.2b) and 2005 (Figure 6.2c). According to a report for the National Parks and Wildlife service, the lake was drained in the early 1920s (Goodwillie *et al*., 1992). Additional evidence for the drainage of Lough Ballygawley in the 19th century exists in a document entitled ‘The Lake dwellings of Ireland: or Ancient Lacustrine Habitatations of Erin, commonly called Crannogs’, where it is stated that; “The highest point of the crannóg now stands about five feet above the level of the lake, which has been reduced by three feet in height, as a result of drainage operations carried out by the proprietor, Colonel Cooper” (Woodmartin, 1886: 224).

6.2 LAKE BATHYMETRY

Lough Ballygawley is a shallow lake that displays a sub-rectangular shape (Figure 6.3). The deepest section of the lake is located at its centre (1.1 m) where the core was extracted. The transition from this deepest region of the lake (1.1 m) to the shallowest zone (< 0.3 m) is marked by gentle slopes on all sides. On the southern section of the lake, a large shallow shelf is evident that ranges from a depth of 0.5 m to < 0.3 m. A mound of land protrudes from the lake just north of this large shallow zone. This man-made artificial island, traditionally called a *crannóg*, was formally a Medieval dwelling (Edwards, 2013) and has been inactive over the time period of interest in this study. The northeastern section of the lake has an active input stream, and two small output streams are present, with one on the southern edge and one on the western edge of the lake.

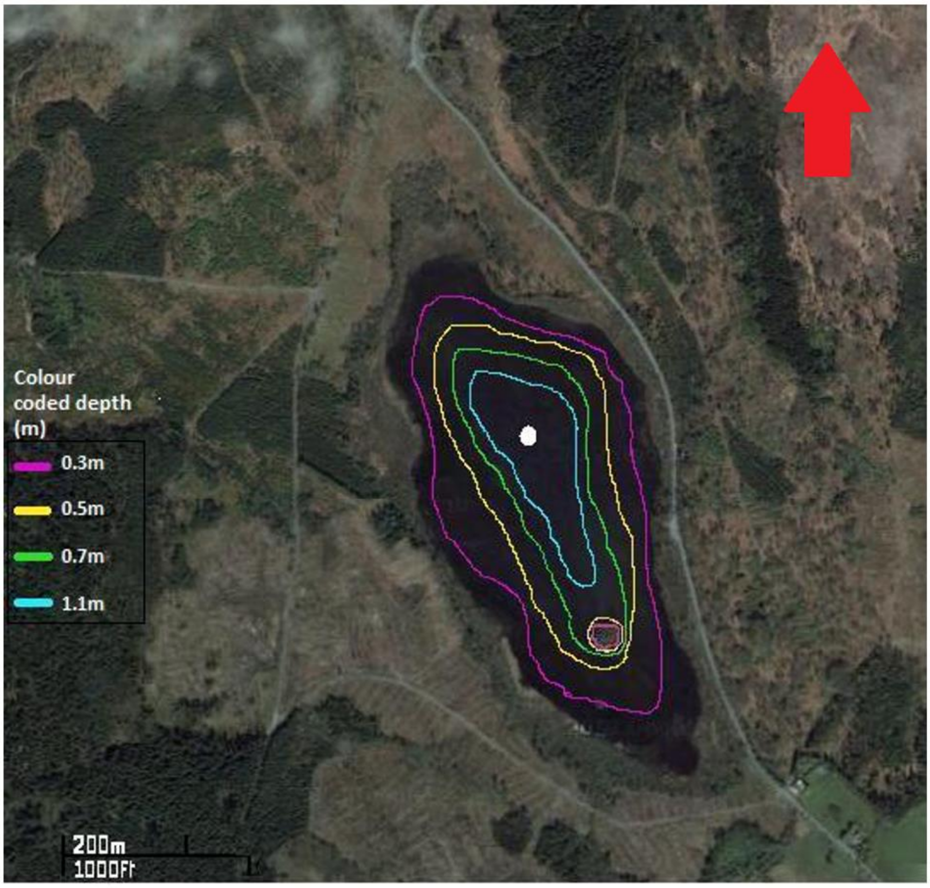


Figure 6.3 Bathymetric map of Lough Ballygawley. White circle marks point where sediment cores were extracted.

6.3 LAKE SEDIMENT CHARACTERISTICS AND LOI

Two replicate cores were recovered from the centre of Lough Ballygawley. They were uniform in appearance, both consisting of dark brown gyttja in the upper surficial 9.5 cm. The first core was 23.5 cm in length, while the second was 21.5 cm. The longer core was designated the master core and the sediment from this core was used for radiometric dating, LOI and chironomid extraction. LOI results will be discussed solely in terms of organic carbon (LOI 550˚C) as inorganic carbon (LOI 950˚C) remains low and relatively constant throughout the core. Organic carbon values range from 34% to 71% (Figure 6.4). Organic carbon values remain relatively stable with an average of ~55% between 23.5 cm and 15 cm. The level of organic carbon abruptly changes at around 15 cm until it reaches a peak of 71% at 13 cm.

Hereafter, organic carbon values plummet to ~50% by 11 cm. A further drop takes place at 9.5 cm to reach value of 33%, where organic carbon remains stationary until an increase to 50% at 8 cm. There is a minor increasing trend for the remainder of the core.

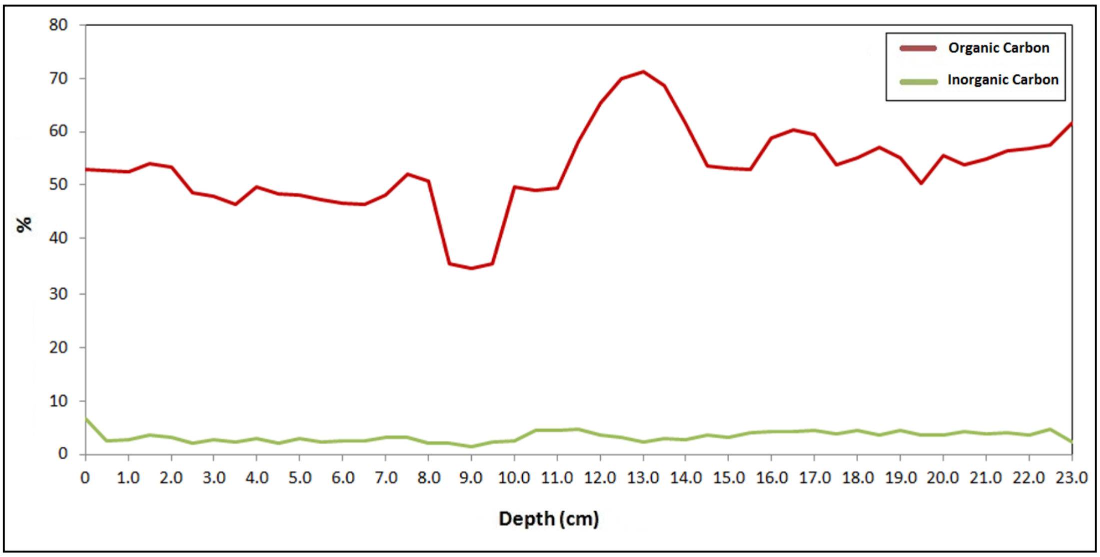


Figure 6.4 Organic and inorganic content for the entire sediment core of Lough Ballygawley.

6.4 DATING MODEL

6.4.1 ^{210}Pb Chronology

The top 12 cm section of core A was datable by ^{210}Pb and represents 1878 to 2009. The results of the ^{210}Pb age-depth model are displayed in Figure 6.5. Standard errors (SE) of ^{210}Pb dates ranged from 98 years at the bottom of the chronology to approaching zero error at the top of the core. SE of ^{210}Pb dates between 1980 and 2009 ranged from 7 years to approaching 0 years.

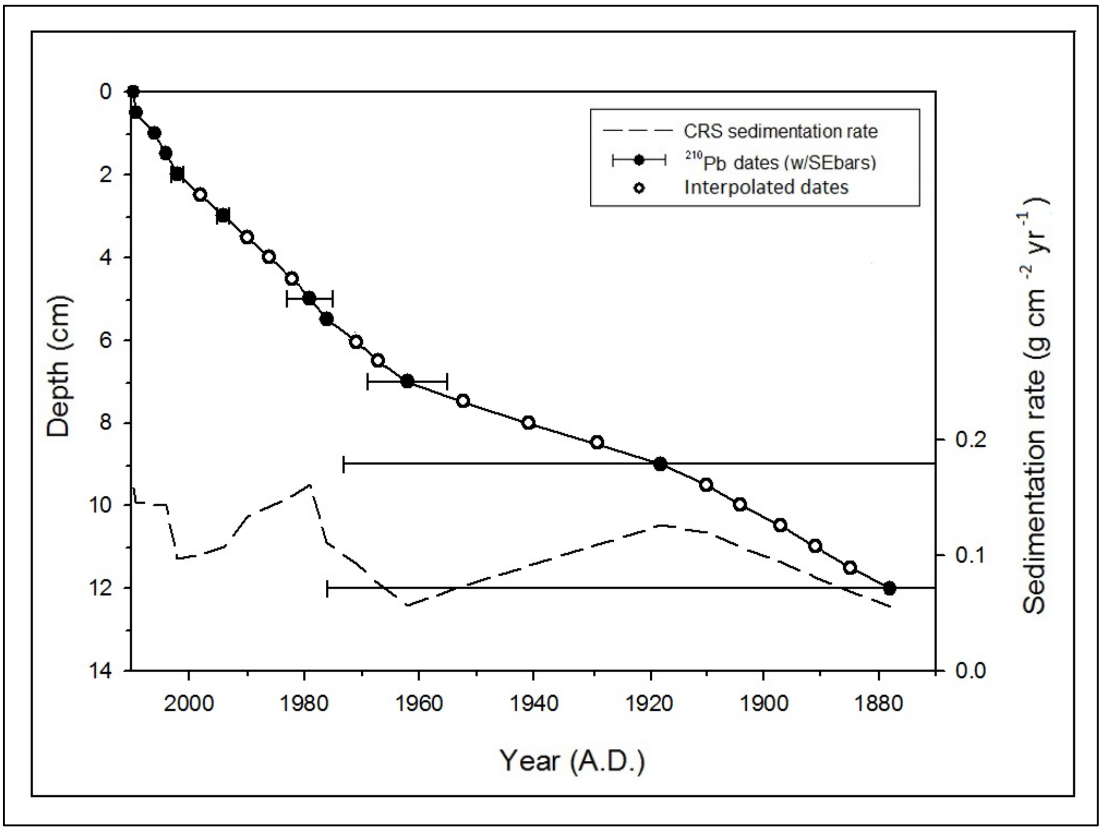


Figure 6.5 ^{210}Pb age-depth model Lough Ballygawley utilising the CRS (constant rate of supple) model.

Sedimentation rates vary considerably over this dated section of the core. The mean dry mass accumulation rate (DMAR) between 1878 until 1918 was 0.163 g $cm^{-2}yr^{-1}$ (6 yr cm^{-1}). A subsequent decrease in DMAR occurred between 1929 and 1962 at 0.100 g $cm^{-}yr^{-1}$ (10 yr cm^{-1}). The 1960 to 2009 period displays enhanced variability in DMAR. Rates increase over the short period spanning 1967 to 1971 at 0.420 g $cm^{-2}yr^{-1}$ (2.5 yr cm^{-1}), before escalating to 0.420 g $cm^{-2}yr^{-1}$ (2 yr cm^{-1}), between 1976 and 2002. The most recent portion of the sediment core spans 2004 to 2009 and displays a sharp increase in DMAR to 1.030 g $cm^{-2}yr^{-1}$ (1 yr cm^{-1}).

6.4.2 ^{14}C Dating Problems

Two AMS radiocarbon dates of humic acid fraction of bulk sediment were obtained for Lough Ballygawley. One sample was taken from the top of the core, while a second was taken from the bottom at a depth of 22 to 22.5 cm. The top sample was ^{14}C-dated to test if a reservoir effect was present in the lake, due to the underlying calcareous bedrock. The two radiocarbon dates were, again, erroneously old. The top sample was yielded an age of 760 cal. yr BP, while the sample at 22-22.5 cm was found to lie between 2,111 and 2,267 cal. yr BP. Lough Ballygawley is fed by an inlet river which drains a bog area, and it is likely that the peat material from the surrounding catchment is entering the lake. This sediment contains already partially decayed ^{14}C humic acid compounds, essentially contaminating in-lake sediment layers by reworking older material through newer sediments (Watson *et al*., 2010). This would distort the levels of ^{14}C within lake sediments (Shore *et al*., 1995). Subsequently, ^{14}C dates were deemed unreliable and were not used for further analysis. The background presence of carbonates in the lake sediment (average 4-5% by weight) would also result in erroneously old ^{14}C dates in the bulk sediment (Shore *et al*., 1995).

6.5 TEMPERATURE DATA LOGGERS

Three years of hourly water temperature data was collected over the period October 2009 to October 2012. Air temperature was also collected at one hour intervals from October 2009 to October 2011. From these datasets, mean daily temperatures were calculated. The values for air and water follow similar daily rates of warming and cooling over the two years of recording from October 2009 until October 2011 (Figure 6.6). Maximum values for both air and water temperature were reached in the months of June, July and August. Mean surface water temperatures shows higher values than mean air temperatures in summer. This is due to exchange of latent heat between the atmosphere and the water combined with greater thermal carrying capacity of surface lake water during these warmer months (Livingstone and Lotter, 1998).

Mean daily air temperatures from the data loggers follow a similar rate of warming and cooling with the Markree maximum, minimum and mean daily record between April 2010 and September 2010 (Figure 6.7). The data logger for collecting air temperature was protected from direct sunlight by placing the equipment under the shade of the tree on the north-facing side of the truck. Mean daily air temperature collected using the data logger were slightly higher (~0.871ºC between April-September 2010) than the mean daily air temperature at Markree Observatory.

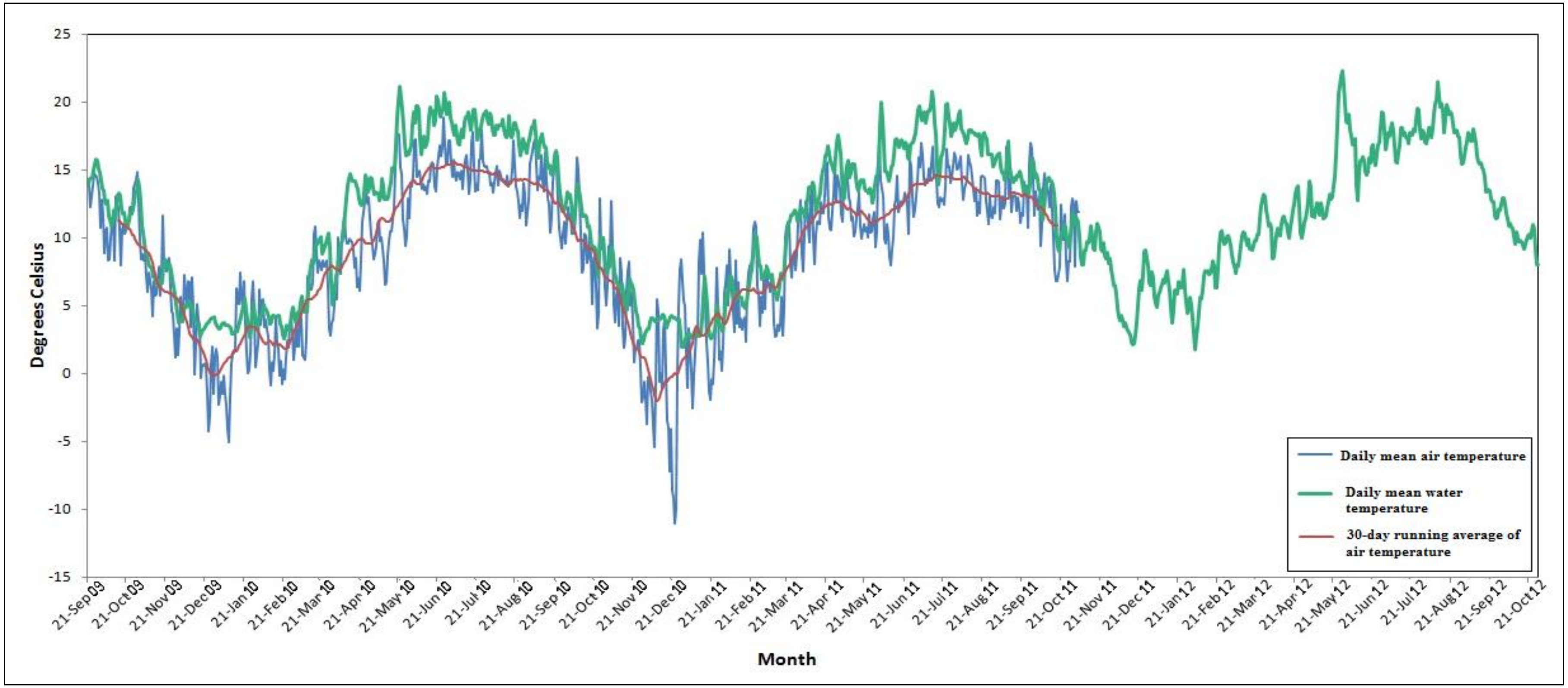


Figure 6.6 Mean daily air temperatures calculated from the average of the 24 hour readings over the entire recording period of three years (September 2009 to October 2012) collected using an air temperature data logger.

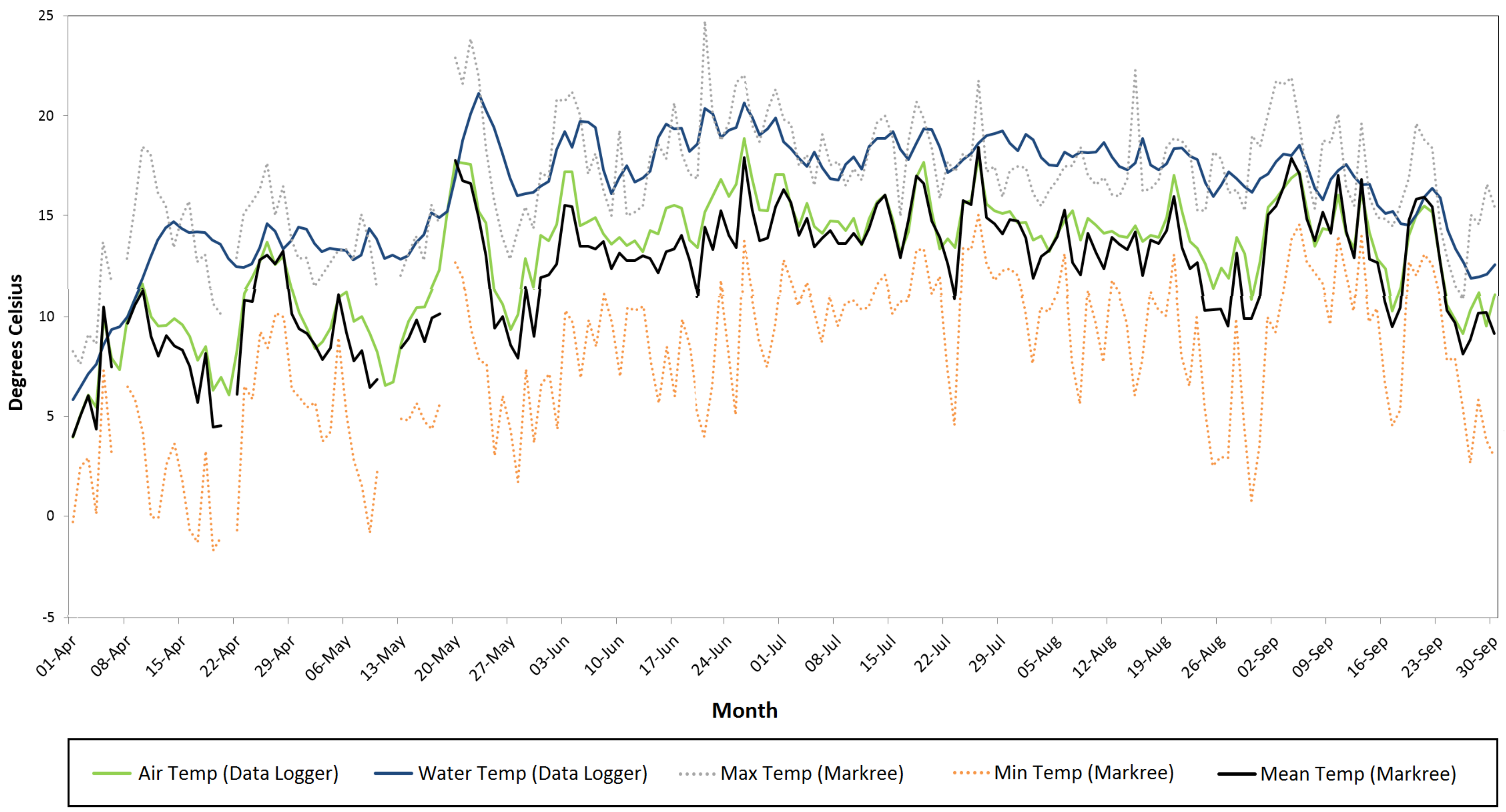


Figure 6.7 Daily mean air temperatures recorded from April 2010 to September 2010 compared with the daily maximum, minimum and mean temperatures from the Markree Observatory record over the same period.

As Lough Ballygawley and Markree Observatory are located at the similar elevations 26 m a.s.l and 35 m a.s.l., respectively), the difference in air temperature is likely due to katabatic air drainage in the Ballysadare catchment where Markree Observatory is located (McKeown *et al*., in press).

6.6 CHIRONOMID COMMUNITY COMPOSITION

In this section, the results from the Lough Ballygawley chironomid stratigraphy will be discussed in terms of the entire core (Figure 6.8). In the previous chapter, the entire core and ^{210}Pb-dated segment of Lough Meenagraun were discussed separately. As the dated section of the Lough Ballygawley core spans most of the sediment core, the core will be discussed in its entirety in order to avoid repetition. Also, zonation was unchanged when focusing solely on the dated section of Lough Ballygawley, which was not the case with Lough Meenagraun. A total of 57 species were identified throughout the core, with an average of 18 taxa per sample. Out of the 57 species identified, 20 were deemed rare. The chronology was divided into four zones, where only two were significant, zone 1 and zone 2. Head capsule concentrations varied widely throughout the core with 14 to 46 head capsules ml^{-1} of wet sediment. A minimum of 50 head capsules enumerated for every sample. Head capsule concentrations are highest in zones 2 and 4, and lowest in zone 3. The Shannon-Wiener Diversity Index ranged between 2.5 and 5.4 throughout the core. The greatest level of diversity was observed in zone 3, while zone 1 marked the lowest diversity levels.

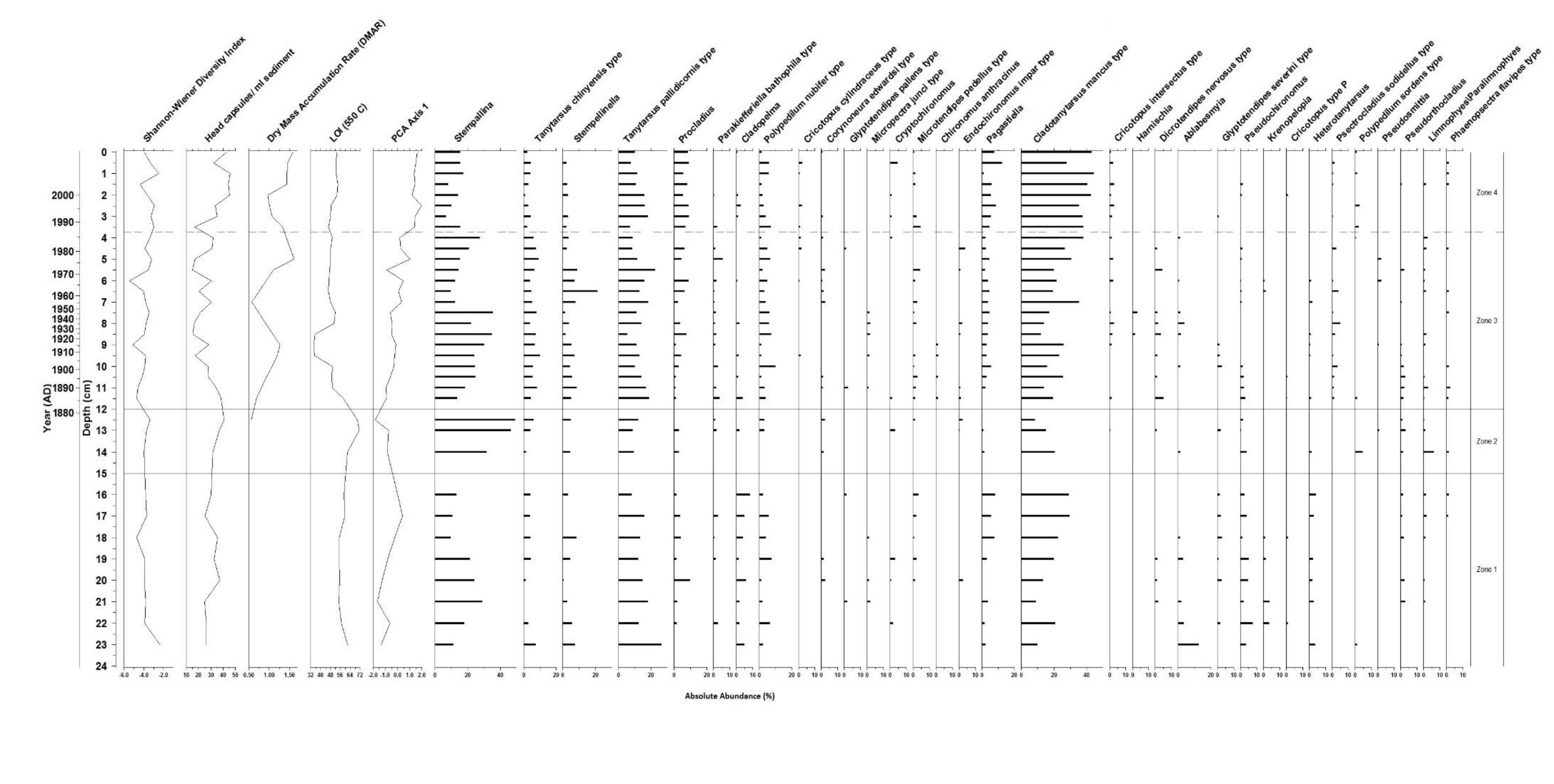


Figure 6.8 Chironomid stratigraphy of important taxa and community zonation for Lough Ballygawley. LOI (550˚C), Shannon-Wiener Diversity of each sample, Axis 1 scores from Principal Component Analysis (PCA) of chironomid data, and summer air temperatures inferred using Potito *et al.*, (forthcoming) transfer function with LOESS smoother (span = 0.2).

As was carried out on Lough Meenagraun, taxa ecology was determined using Wiederholm (1983), Rieradevall and Brooks (2001) and Brook *et al*. (2007), and ecological preferences identified in the Irish training set (Potito *et al.*, forthcoming).

6.6.1 Zone 1 (23 cm – 15.5 cm)

Warm water taxa comprise ~30% of the total taxa in zone 1. *Cladotanytarsus mancus*-type (19%), *Pagastiella* (4%) and *Ablabesmyia* (3%) are the most prominent taxa in this group, with smaller populations of *Pseudorthocladius* and *Glyptotendipes severini*-type (Potito *et al*., forthcoming). These taxa display an overall increase throughout this zone, but show a notable decline between 22 cm and 20 cm in depth. Taxa associated with cooler, less productive lake conditions, primarily *Krenopelopia,* show an increase between 22 cm and 20 cm. *Krenopelopia* enters the zone for the first time at 22 cm reaching levels of 4%, with *Cricotopus* type-*P* following a similar trend.

Fauna associated with eutrophic lake conditions comprise ~32% of the total taxa in this zone. *Tanytarsus pallidicornis*-type (15%), *Cladopelma* (4%), *Polypedilum nubifer*-type (4%) and *Procladius* (3%) compose the majority of this group. These taxa show an overall increase throughout this zone. Low levels of *Endochironomus impar*-type and *Micropsectra junci*-type appear at 20 cm depth. Interestingly, *Stempellina*, which is associated with oligotrophic water conditions, increases in this first section of the zone from levels of around 11% to 29%, before decreasing throughout the rest of the zone. *Stempellinella,* which is associated with more mesotrophic conditions, is abundant at the beginning of this zone (8%), and declines to <1% at 20 cm in depth. A subsequent increase to 9% at 18 cm in depth is notable, in line with other taxa associated with more productive lake conditions.

Limnophyes/Paralimnophyes, which is indicative of terrestrial/semi-terrestrial environments, is present at levels of around 3.5%. *Phaenopsectra*, associated with shallow littoral environments, is also present at 3%. Both taxa display an increase in population in the second half of this zone. *Heterotanytarsus*, which is associated with brown humic water, is also present in the zone, albeit at low levels. Finally, this zone is marked by the highest level of head capsule concentration at 37 head capsules ml^{-1} of wet sediment. Shannon-Wiener Diversity Index values are also high at an average of 3.8. Organic content remains relatively consistent throughout this zone, averaging around 56%.

6.6.2 Zone 2 (15 cm – 12.5 cm)

Zone 2 is marked by an increase in taxa associated with less productive lake conditions (47%). *Stempellina* (43%) accounts for the majority of this change and increases from 32% to 49% over this short zone. The zone is further characterised by a decrease in taxa linked with eutrophic water conditions (21%), such as *Tanytarsus pallidicornis*-type (10%), *Polypedilum nubifer*-type (2%), *Procladius* (2%), *Cladopelma* (<1%), *Glyptotendipes pallens*-type (absent) and *Microtendipes pedellus*-type (<1%). *Stempellinella* drops to levels of 3% in this zone, indicating a notable shift in trophic status.

Limnophyes/Paralimnophyes, which is linked with terrestrial/semi-terrestrial environments, increases at the beginning of the zone to levels of 6%. This taxon declines to <1% through the rest of this zone. Warm water taxa show an overall decline to around 22% in this zone. The primary taxon in this group is *Cladotanytarsus mancus*-type, showing a notable decline through the zone (21% to 9%). Head capsule concentrations are at their lowest in this zone, reaching levels of 25 head capsules ml^{-1} of wet sediment. Species diversity remains similar to the previous zone at 3.8. Organic content increases throughout this zone, with an average of 65%. The end of this zone marks the beginning of the ^{210}Pb-dated chronology.

6.6.3 Zone 3 (11.5 cm – 4 cm, AD 1884 – AD 1985)

In zone 3, taxa associated with oligotrophic lake conditions, namely *Stempellina*, decrease to 21%, while concentrations of taxa associated with more eutrophic conditions increase to 27%. *Stempellina* is prominent in the first half of this zone (1880 to 1940) and decreases in the second half (1950 to mid-1980s). Taxa which have been linked with agricultural activities in an Irish context (Potito *et al.*, forthcoming), such as *Tanytarsus pallidicornis*-type (13%), *Procladius* (3%) and *Polypedilum nubifer*-type (4%), remain at high levels in this zone, with the highest levels post-1950 to the mid-1980s. Other taxa associated with these lake conditions include *Parakiefferiella bathophila*-type, *Cladopelma*, *Chironomus antracinus*-type, *Endochironomus impar*-type, *Glyptotendipes pallens*-type, *Microtendipes pedellus*-

type, *Micropsectra junci*-type, *Harnischia* and *Corynoneura edwardsi*-type. Although these taxa are present at low levels, they highlight the species diversity that exists among taxa associated with agricultural activities. Furthermore, *Stempellinella* comprises 6% of the taxa in this zone and displays a notable increase between the mid-1950s and the early-1970s. This taxon is associated with more mesotrophic conditions and the peak in abundance in the early 1960s mirrors the lull in levels of *Stempellina* at this time.

Taxa associated with warm water conditions increase in this zone to an average of 31%. *Cladotanytarsus mendax*-type (23%) is the dominant taxon in this group, and displays a general increasing trend throughout the zone, with the greatest concentrations from the mid-1950s until mid-1980s. This taxon reaches its lowest level from the mid-1920s to mid-1940s, while *Cricotopus intersectus*-type and *Ablabesmyia* display an increase in numbers over the same time period. *Pagastiella* is also present in this zone, albeit at low numbers. Finally, taxa associated with terrestrial/semi-terrestrial environments, such as *Limnophyes/Paralimnophyes* and *Pseudorthocladius* are present at levels of 5%. These taxa are most abundant in the initial portion of this zone (between mid-1880s and early-1900s), with lower levels characterising the remainder of the zone. This zone displays the highest Shannon-Wiener Diversity Index values with an average of 4.1. Head capsule concentrations increase in this zone to levels of 36.4 head capsules ml^{-1} of wet sediment. Organic content is marked by an initial falling trend for the first third of this zone, reaching its lowest levels between 8.5 cm and 9.5 cm (1910 to the mid-1920s).

6.6.4 Zone 4 (3.5 cm – 0 cm, AD 1988 – AD 2009)

This zone is dominated by warm water taxa, accounting for 47% of total chironomids. *Cladotanytarsus mancus*-type is the most prominent taxa in this group, composing 39% of the fauna in this zone. This species remains consistently high throughout the zone, reaching maximum levels of 44% in 2006. Other taxa associated with warmer lake conditions, such as *Pagastiella,* comprise a further 7% of the taxa in this zone.

Taxa associated with cooler, less productive lake conditions, such as *Krenopelopia*, are absent in this zone. Eutrophic taxa linked with agricultural activities remain at relatively similar levels to zone 3 (28%). Taxa associated with oligotrophic conditions, namely *Stempellina* and *Tanytarsus chinyensis*-type, fall to levels of 13% and 3% respectively. Furthermore, *Stempellinella* drops to ~2% in this zone, decreasing progressively before disappearing from the stratigraphy in 2008. This zone is characterised by the lowest level of species diversity at 3.4. Head capsule concentrations fall to 29.8 head capsules ml^{-1} of wet sediment, while organic content remains stable at ~51%.

6.6.5 Community Compositional Change

Samples in the first zone are clustered at the bottom of the bi-plot (Figure 6.9) and are composed of taxa associated with cooler waters, eutrophic lake conditions and brown waters. Important taxa include *Cladopelma*, *Cricotopus* type *P*, *Heterotanytarsus* and *Tanytarsus pallidicornis*-type (Figure 6.10). Samples in zone 2 shift to the top portion of the bi-plot (Figure 6.9). These samples are dominated by taxa associated with warmer water conditions. The taxa include *Dicrotendipes nervosus*-type and *Endochironomus impar*-type. These samples contain a high abundance of *Stempellina*, which indicates less productive lake conditions at this time. *Limnophyes/Paralimnophyes* is also dominant in these samples. As this taxon is linked with terrestrial/semi-terrestrial lake environments it is possible that lake levels changed significantly at this time. Furthermore, eutrophic taxa such as *Micropsectra junci*-type indicate that the lake is still supporting taxa associated with eutrophic waters.

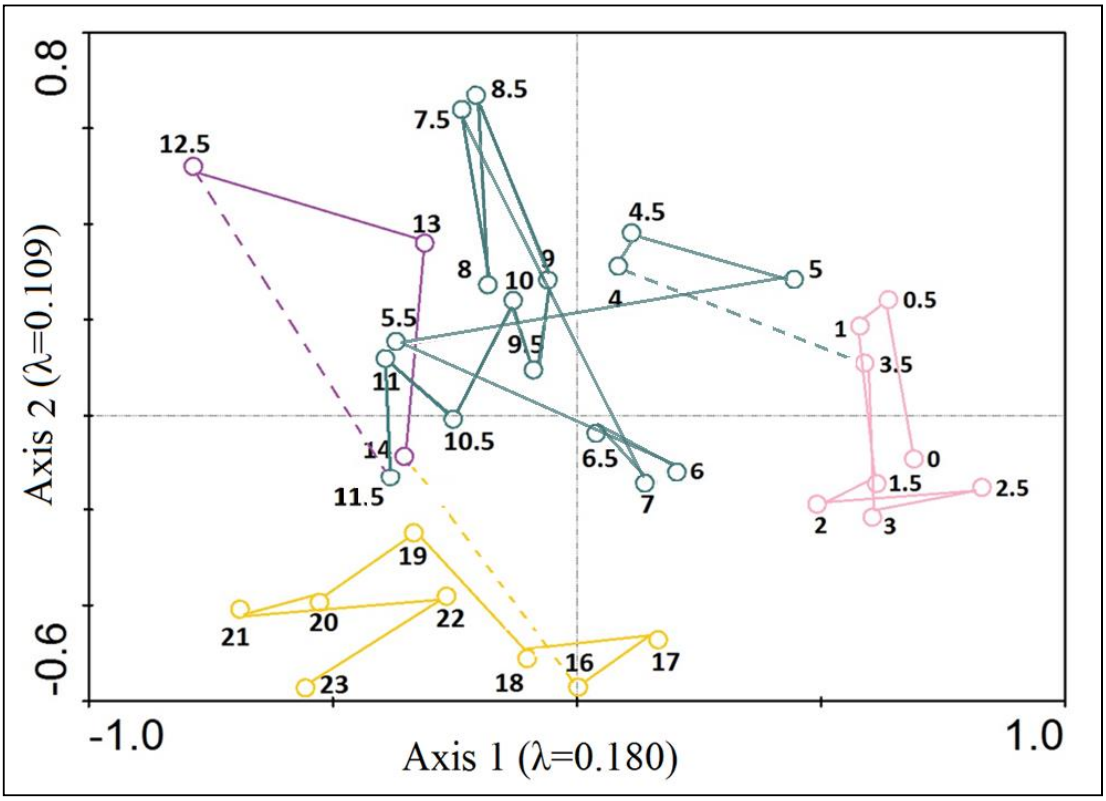
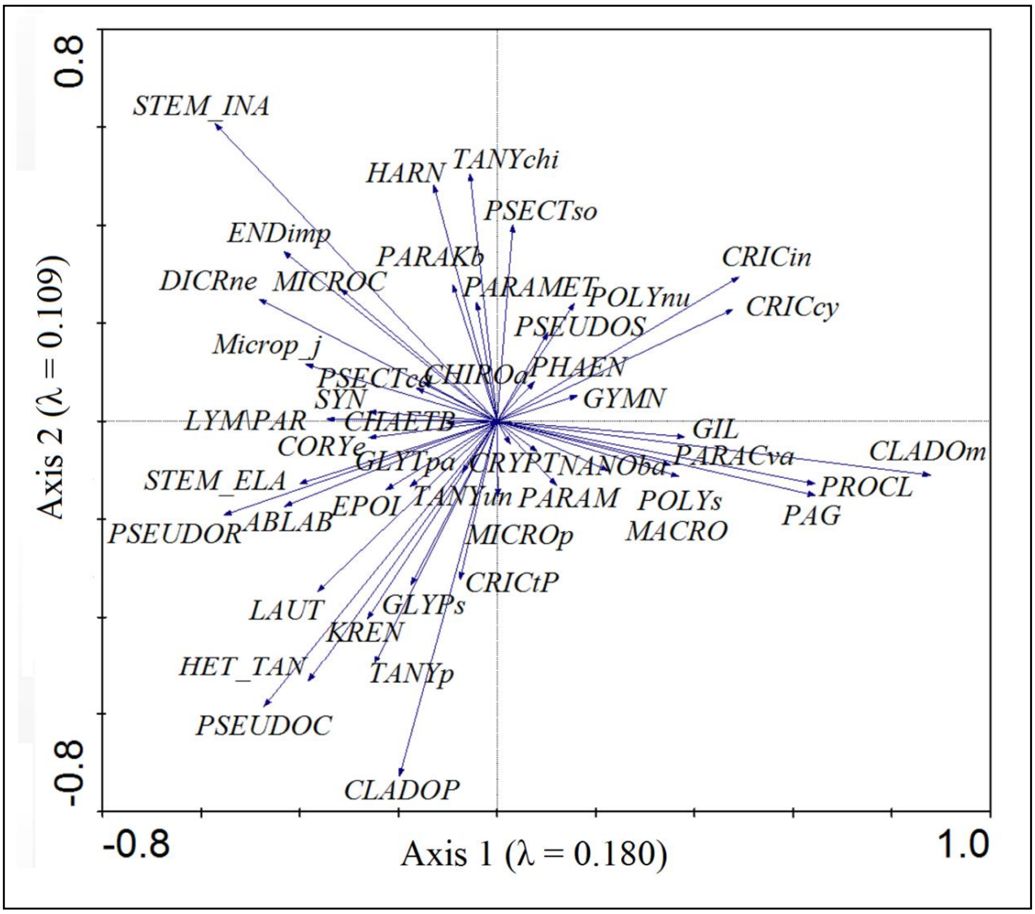


Figure 6.9 Principal component analysis (PCA) bi-plot for chironomid samples displaying changes in chironomid trajectory (chironomid zones from Figure 6.8 are highlighted in different colours on this graph). Circles indicate different depths (cm).

The shift across PCA Axis 1 ($\lambda = 0.180$), from samples encompassing zone 1 to zone 3, can be explained by a transition from taxa associated with intermediate temperatures and mesotrophic to oligotrophic lake conditions towards taxa linked with eutrophic lake conditions and warmer temperatures. The taxa which illustrate this shift are primarily *Cladotanytarsus mancus*-type, *Procladius*, *Cricotopus intersectus*-type, *Cricotopus cylindraceus*-type and *Pagastiella* (Figure 6.10)



Legend

Code name	Taxa full name	Code name	Taxa full name
ABLAB	*Ablabesmyia*	*MICROc*	*Microchironomus tener*-type
CHIROa	*Chironomus anthracinus*-type	*MICRp*	*Microtendipes pedellus-type*
CLADOm	*Cladotanytarsus mancus*-type	*NANOba*	*Nanocladius balticus*-type
CLADOP	*Cladopelma*	*PAG*	*Pagastiella*
CORYe	*Corynoneura edwardsi*-type	*PARACva*	*Parachironomus varus*-type
CRICcy	*Cricotopus cyclindraceus*-type	*PARAKb*	*Parakiefer iella bathophila*-type
CRICin	*Cricotopus intersectus*-type	*PARAM*	*Paramerina*
CRICtP	*Cricotopus* type P	*PARAMET*	*Parametriocnemus*
CRYPT	*Cryptochironomus*	*PHAEN*	*Phaenopsectra*
DICRne	*Dicrotendipes nervosus*-type	*POLYnu*	*Polypedilum nubifer*-type
ENDimp	*Endochironomus impar*-type	*POLYs*	*Polypedilum sordens*-type
EPOI	*Epoicocladius*	*PROCL*	*Procladius*
GIL	*Gillotia*	*PSECTca*	*Psectrocladius calcaratus*-type
GLYPs	*Glyptotendipes severini*-type	*PSECTso*	*Psectrocladius sordidellus/psiloperus*-type
GLYTpa	*Glyptotendipes pallens*-type	*PSEUDOR*	*Pseudorthocladius*
GYMN	*Gymnometriocnemus*	*PSEUDOS*	*Pseudosmittia*
HARN	*Harnischia*	*STEM_ELA*	*Stempellinella*
HET_TAN	*Heterotanytarsus*	*STEM_INA*	*Stempellina*
KREN	*Krenopelopia*	*SYN*	*Synorthocladius*
LAUT	*Lauterborniella*	*TANYchi*	*Tanytarsus chinyensis*-type
LIM\PAR	*Limnophyes/Paralimnophyes*	*TANYp*	*Tanytarsus pallidicornis*-type
MACRO	*Macropelopia*	*TANYun*	*Tanytarsus* undiffrenciated

Figure 6.10 PCA bi-plot of common chironomid taxa.

PCA was performed on the ^{210}Pb-dated portion of the core, in order to gauge chironomid community change over the recent past. In Figure 6.11, the year 1878 marks the end of zone 2. This sample is dominated by taxa associated with oligotrophic lake conditions, such as *Stempellina* and *Tanytarsus chinyensis*-type, while taxa linked with eutrophic conditions, such as *Endochironomus impar*-type are still present (Figure 6.12).

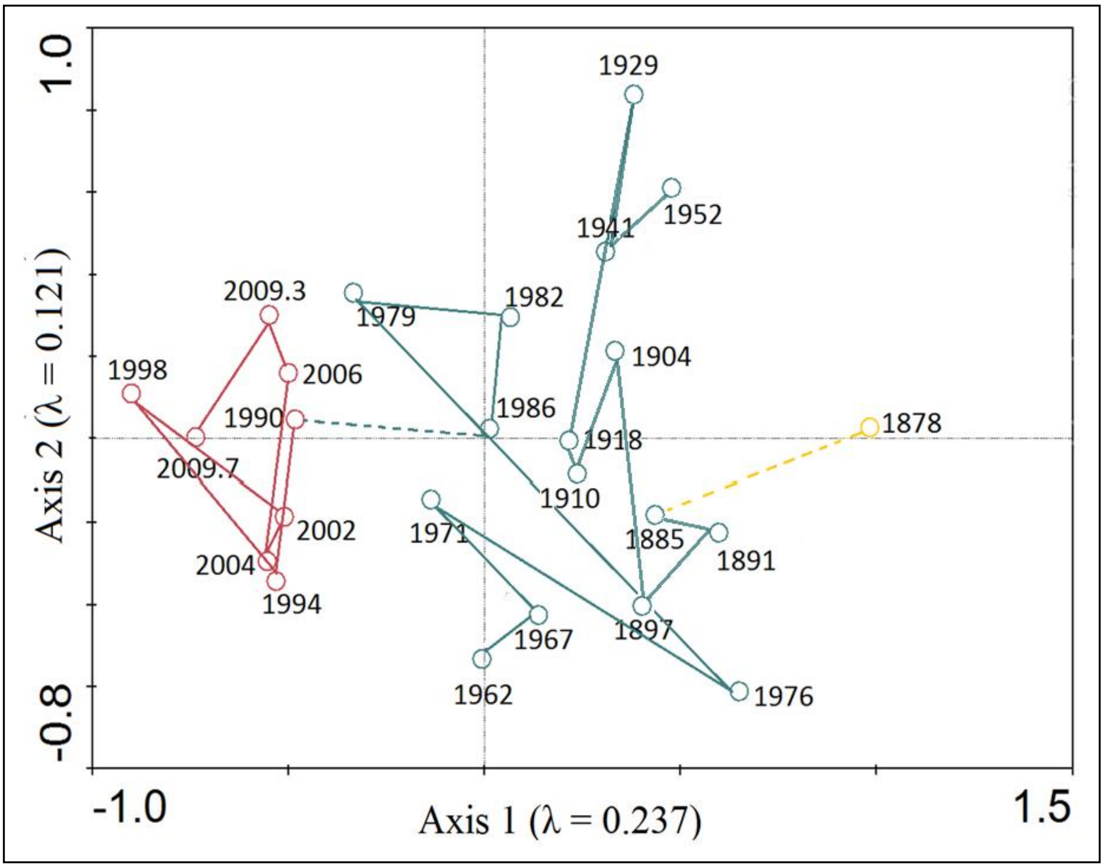


Figure 6.11. Principal component analysis (PCA) bi-plot for chironomid samples displaying changes in chironomid trajectory over the ^{210}Pb-dated section (chironomid zones from Figure 6.8 are highlighted in different colours on this graph). Circles indicate different depths (cm).

Samples in the upper right quartile of the graph encompass the early- to mid-20th century (Figure 6.11), contain a high abundance of eutrophic taxa such as *Harnischia*, *Polypedilum nubifer*-type and *Micropsectra junci*-type.

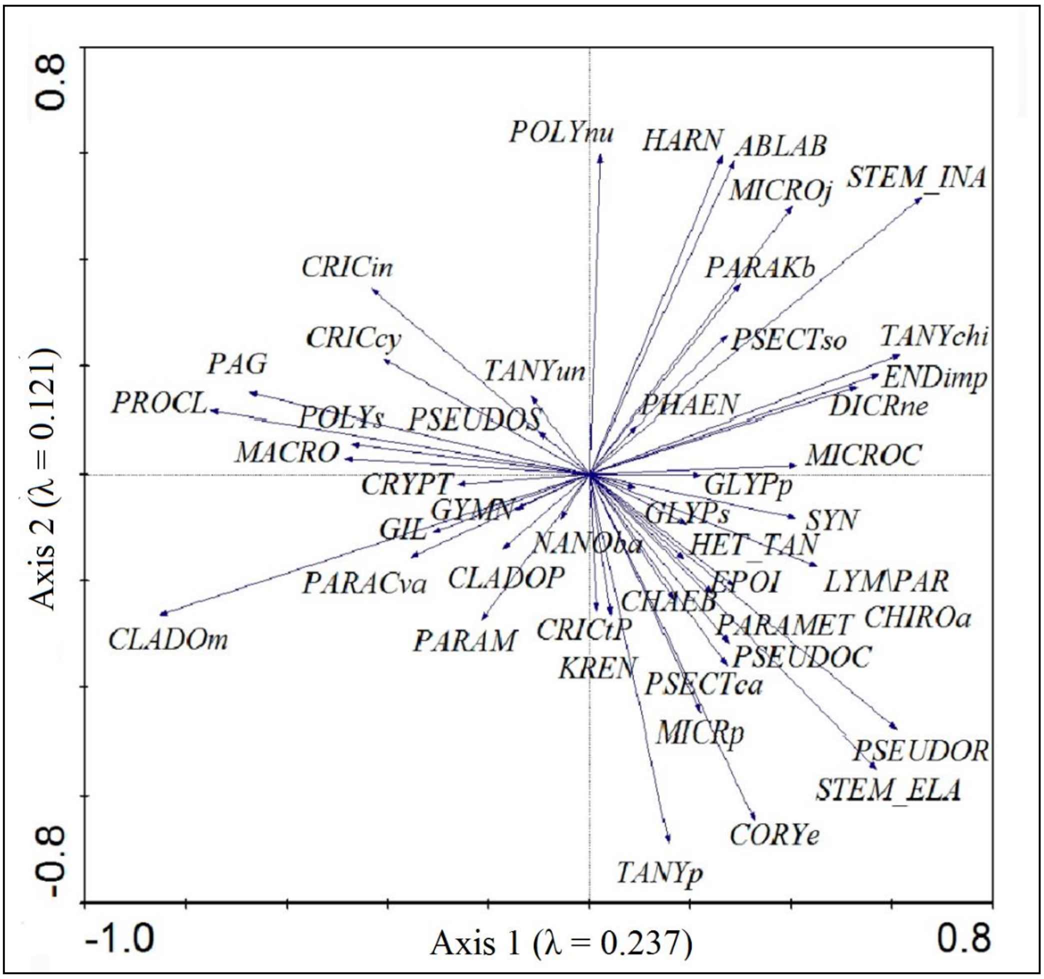


Figure 6.12 PCA bi-plot of common chironomid taxa from the ^{210}Pb-dated section of the sediment core. Refer to legend from Figure 6.10.

The shift in samples towards the lower right quartile of the bi-plot (1962 to 1976) marks a movement to colder conditions, as indicated by the greater abundance of Krenopelopia in these samples (Figure 6.12). However, lake conditions remain eutrophic with the presence of high levels of *Tanytarsus pallidicornis*-type, *Corynoneura edwardsi*-type and *Microtendipes pedellus*-type in the samples.

Finally, samples that span the late 20th century and early-21st century are clustered towards the left of Figure 6.11. These samples are dominated by taxa associated with warm lake conditions, such as *Cladotanytarsus mancus*-type, *Cricotopus intersectus*-type, combined with taxa linked with eutrophic lake environments, such as *Procladius*, *Pagastiella* and *Cricotopus cylindraceus*-type (Figure 6.12). This indicates a movement towards warmer, more eutrophic lake conditions throughout the late 19th century to early 21st century, with a number of cooler phases identified in the lake.

6.7 CHIRONOMID-INFERRED TEMPERATURE RECONSTRUCTION

The chironomid-inferred temperature (C-IT) reconstructions are presented in Figure 6.13. C-IT ranged from 14.3°C to 15.3°C over the entire chironomid stratigraphy, and a notable warming trend is evident throughout the record. A LOESS smoother (span = 0.20) was applied to the C-IT reconstruction in order to emphasise the main trends within the data. A span of 0.2 was chosen as there are more samples in the stratigraphy. The warmest years span the mid-1980s to 2009, while cooler C-ITs are present in the late 19th and early 20th centuries. The time period between the mid-1980s to 2009 displays a rate of warming of 0.2°C. A slight decline in C-ITs in the early 21st century subdues the rate of inferred warming.

To assess the sensitivity of chironomid community to long term temperature and precipitation change, data from Markree Observatory was compared to the limnological information. Lough Ballygawley is the closest lake to the Markree climate station and local temperature differences between the two locations were assessed using air temperature data loggers. While rates of daily temperature change were similar at the both sites, Markree Observatory displays slightly cooler mean air temperatures, likely due to katabatic air drainage within its catchment. Markree temperature and precipitation data were adjusted to match the resolution of the lake data. Each 0.5 cm section of the lake sediment represents between one and five years of sedimentation after 1962. Each 0.5 cm section of the sediment in the lower portion of the chronology represents a broader time span, between six and twelve years. The Markree mean summer (June, July and August) temperatures and Markree mean July temperatures were compared to the C-IT. The warmest mean July years within each sample interval over the length of the Markree record were also extracted and compared to the chironomid temperature record. A LOESS smoother (span = 0.20) was then applied to the Markree mean summer and mean July temperature records to identify main trends within the data.

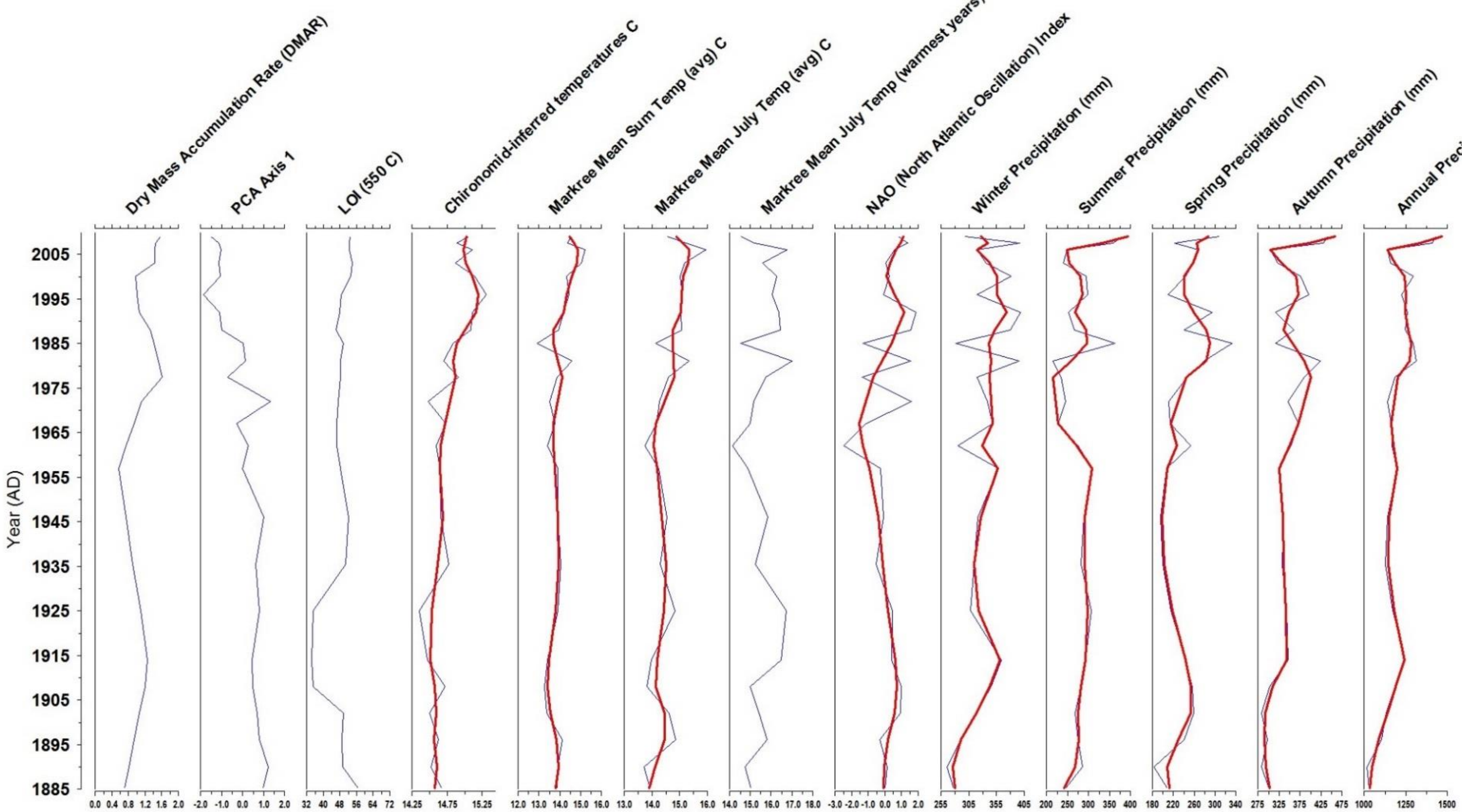


Figure 6.13 Chironomid-based summer air temperature reconstruction, chironomid PCA, LOI, CRS, of Lough Ballygawley and Markree summer temperature, seasonal precipitation and NAO index (with LOESS smoother with a span of 0.2).

Following similar lines of enquiry to the Lough Meenagraun results section, LOESS smoothing was not applied to the record displaying the warmest July years. C-IT follow a similar trend to the Markree mean summer and mean July temperature records. Enhanced warming is evident in all three records after 1985. The C-IT record also follows the record of the warmest July years calculated for each sediment interval. Although trends are similar, the variability experienced in this Markree record is more muted in the chironomid-inferred temperature record. This is likely due to the minor fluctuations in temperature falling within the prediction errors of the chironomid-inference model (RMSEP = 0.51˚C). C-IT model was then extended beyond the scope of the ^{210}Pb-dated section of the core (Figure 6.14), in order to establish longer temperature trends in the more distant past.

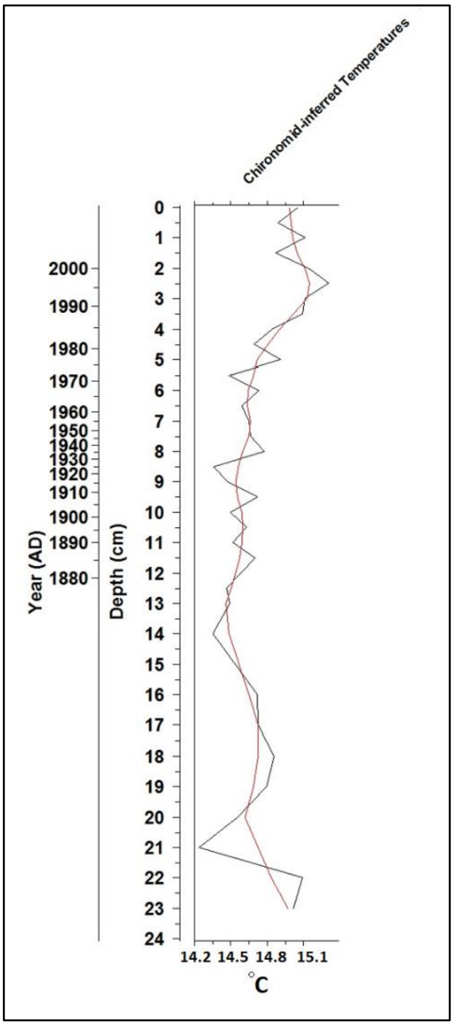


Figure 6.14 Chironomid-inferred temperature reconstruction over the full Lough Ballygawley sediment core.

Anecdotal links were made between C-ITs and calendar years through extending the dry mass accumulation rate of the ^{210}Pb-dating model through the rest of the core. Taking the 1878 to 2009 as the baseline for temperature conditions (14.8°C), a short cooler (14.4°C) period roughly takes place at 14 cm and 12 cm depth (1878 to1850). Beyond this depth, a warm period reaching an average of 14.8°C is evident over the remainder of the record from 16 cm to 23 cm depth (1840 to 1760), although the coldest temperatures in the record are inferred at 21 cm depth (ca. 1790).

6.8 CLIMATE AND LAKE VARIABLES THROUGH TIME

To assess the sensitivity of chironomid community in Lough Ballygawley to recent environmental change PCA Axis 1 scores, organic carbon (550°C) and dry mass accumulation rates (DMAR) were examined along with Markree seasonal and annual precipitation and winter North Atlantic Oscillation (NAO) index values (Figure 6.13). This was carried out to explore the possible environmental controls on the chironomid community through time. Summer temperature appeared to be the most important environmental variable, as a correspondence is evident with C-IT (above) and with inverse values of PCA Axis 1. NAO and precipitation variables seem to have a weaker correspondence with chironomid community change through time.

6.9 REDUNDANCY ANALYSIS (RDA)

As with Lough Meenagraun, five variables were chosen for redundancy analysis (RDA). As the dependable Markree record extends to 1880, analysis was carried out from this date to 2009. The bottom ^{210}Pb-dated sample at 1878 was not included in the analysis as it was outside the scope of the Markree climate records. The five variables selected were summer temperature and LOI, as well as winter, spring and summer precipitation. These five variables explain 27.8% of the chironomid community variance, with RDA Axis 1 and Axis 2 explaining 16.1% and 5.5% of the variance, respectively (Table 6.2). Summer temperature displays the strongest relationship with Axis 1, while LOI shows the strongest affiliation with Axis 2.

Table 6.2 Redundancy analysis (RDA) utilised linear responses showing eigenvalues, species environmental correlations, cumulative percentage variance in species data, canonical coefficients and T-tests.

	Axis 1	Axis 2	Axis 3	Axis 4
Full model				
Eigenvalue	0.161	0.055	0.033	0.028
Species-envt. Corr.	0.845	0.855	0.757	0.754
Cum.% var. Spp.	16.1	21.6	25	27.8
Canonical coefficients				
Summer air temp	0.615	-0.431	0.277	-0.112
LOI	0.244	-0.659	-0.367	0.092
Winter precipitation	0.400	0.218	-0.092	-0.607
Spring precipitation	0.459	0.126	-0.231	0.360
Summer precipitation	0.260	0.502	-0.231	0.360
Significant T-values				
Summer air temp	3.666**	-2.240*	1.356	-0.532
LOI	1.183	-4.109**	-1.853	0.436
Winter precipitation	2.047*	1.050	-0.435	-3.59**
Spring precipitation	2.427*	0.598	-0.733	1.713
Summer precipitation	1.265	2.727*	-1.15	1.812

** $P < 0.01$, * $P < 0.05$
Species-envt. Corr. = species environment correlation for each axis
Cum.% var. Spp. = cumulative percent variance in species data

For chironomid taxa, *Cladotanytarsus mancus*-type (thermophilic), *Macropelopia* (acidophilic), *Procladius* (associated with eutrophic lake conditions), *Polypedilum sordens*-type (associated with macrophytes and eutrophic lake conditions) and *Pagastiella* (thermophilic) are located to the right of Figure 6.15, while *Stempellinella* (associated with oligotrophic to mesotrophic lake conditions) and *Tanytarsus chinyensis*-type (associated with cooler lake environments), are clustered towards the left of the bi-plot. These taxa show the strongest relationship with RDA Axis 1 ($\lambda = 0.161$). Taxa on the left of Axis 1 are associated with cooler temperatures while taxa on the right are indicative of warmer, more productive conditions.

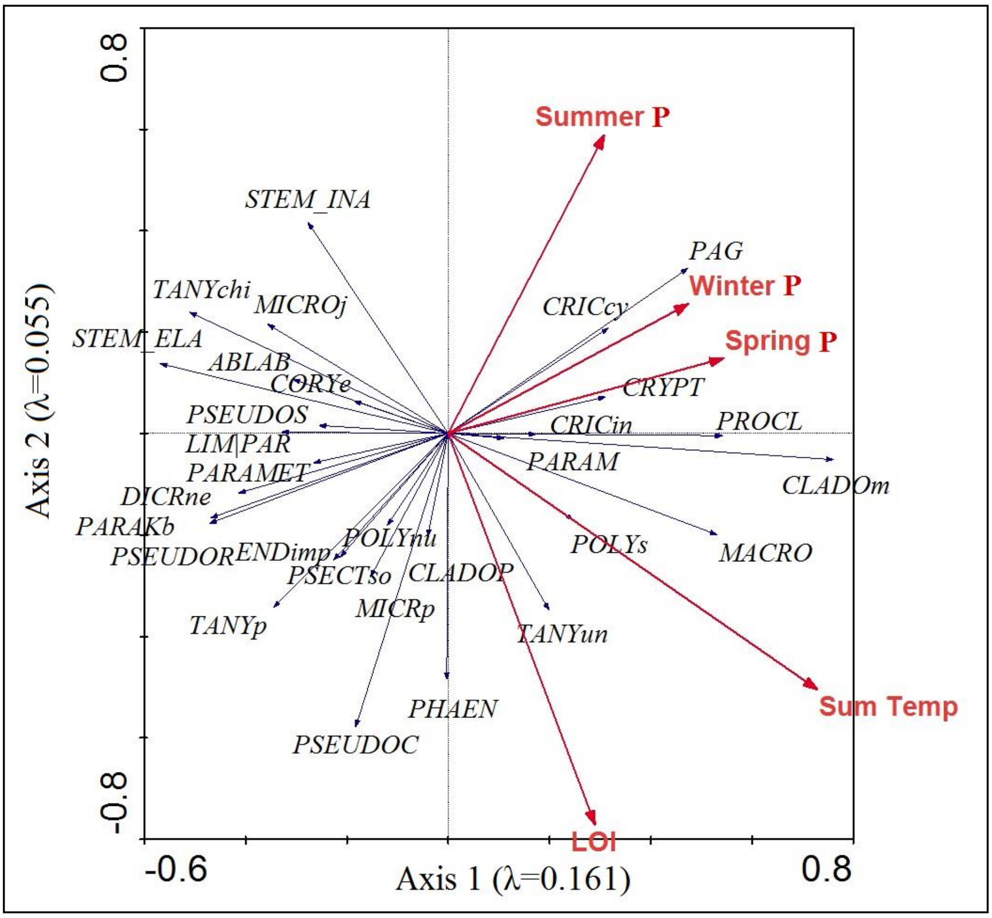


Figure 6.15 RDA bi-plot showing species distribution being influenced by LOI, summer temperature (Sum Temp), winter precipitation (Winter P), spring precipitation (Spring P) and summer precipitation (Sum P). Refer to legend of Figure 6.10.

Samples on the right of Axis 1 (Figure 6.16) reveal warm conditions in the most recent section of the core from 1982 to 2009, while samples on the left of Axis 1 spanning 1885 to 1979, are dominated by cooler, less productive taxa (Figure 6.15). On Axis 2, *Stempellina* is found in its highest abundance in samples spanning 1910 to 1929, in the upper left quartile sample-environment bi-plot. This taxon is associated with oligotrophic lake conditions and is found in samples with lower LOI values. This could indicate that a fall in LOI may be linked with a decrease in the nutrient concentrations in the lake. Historical evidence shows that the lake was drained in the early 20th century (Goodwillie *et al*., 1992), which coincided with a notable fall in LOI and a rise in *Stempellina*. Winter, spring and summer precipitation has less of an influence on chironomid community change than LOI and summer temperature. However, they are still significantly related to the RDA axes with P < 0.05 (Table 6.2).

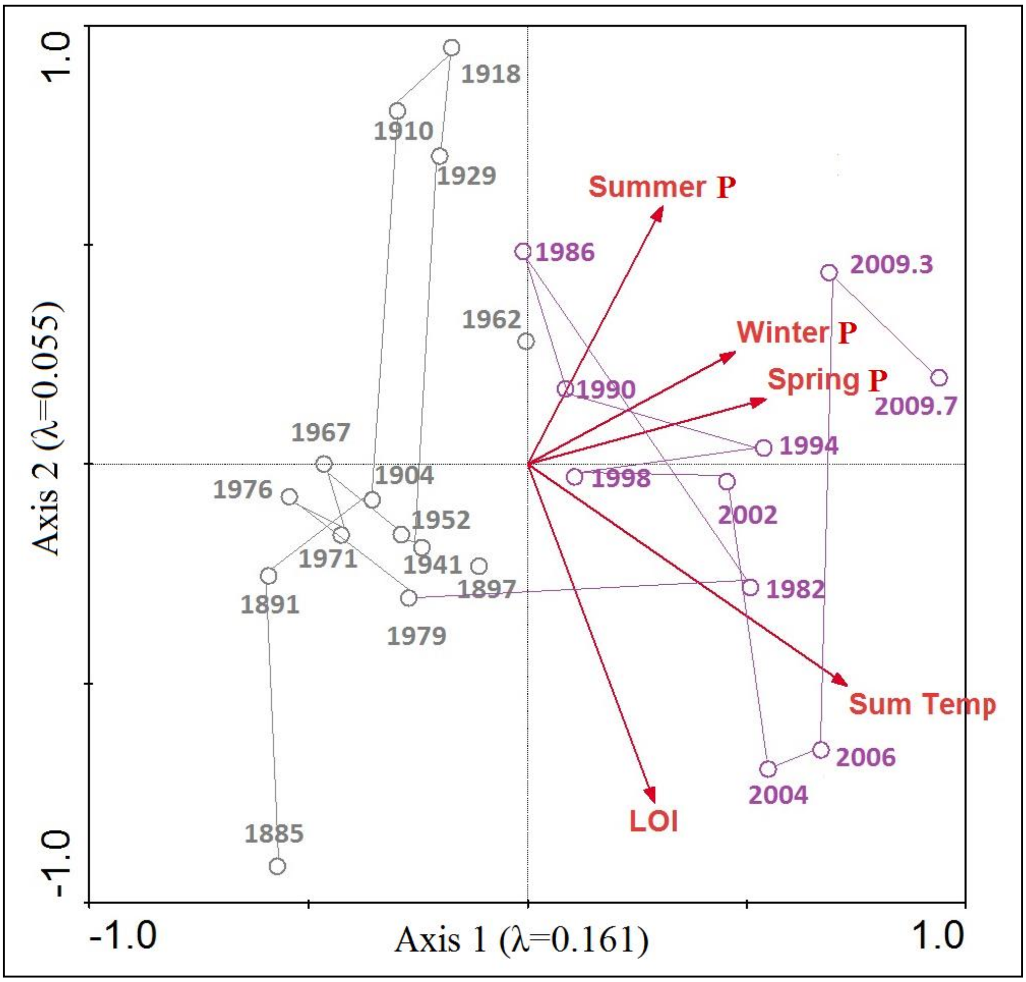


Figure 6.16 RDA bi-plot showing sample distributions influenced by LOI, summer temperature (Sum Temp), winter precipitation (Winter P), spring precipitation (Spring P) and summer precipitation (Sum P).

Partial RDAs indicate that summer temperature is the only significant variable explaining 10.6% of the variance (Table 6.3). This variable exhibits high $\lambda 1/\lambda 2$ ratios due to its strong relationship to RDA Axis 1. Summer temperature became more significant once seasonal precipitation was partialled out (11.3%). Spring precipitation (6.4%), winter precipitation (5.9%), LOI (5.6%) and summer precipitation (4.8%) display weaker relationships with the chironomid community. However, spring and summer precipitation values strengthen when summer temperature is factored out (6.9% and 6.2% respectively). LOI becomes stronger once seasonal precipitation is partialled out (7.2%), while winter rainfall values are strengthened once LOI is factored out.

Table 6.3 Partial RDA for each environmental variable.

Variable	Covariable	λ1	λ1/λ2	P	% variance
Summer Air Temperature	None	0.106	0.589	0.004	10.6
	LOI	0.091	0.508	0.008	9.7
	Seasonal precipitation	0.094	0.672	0.006	11.3
	LOI, seasonal precipitation	0.073	0.545	0.032	9.4
LOI	None	0.056	0.244	0.19	5.6
	Sum temperature	0.041	0.229	0.414	4.6
	Seasonal precipitation	0.06	0.395	0.122	7.2
	Summer temperature, seasonal precipitation	0.039	0.291	0.466	5.2
Winter Precipitation	None	0.59	0.284	0.13	5.9
	Summer temperature	0.044	0.272	0.37	4.9
	LOI	0.065	0.344	0.076	6.9
	Spring and summer precipitation	0.061	0.359	0.13	6.8
	Summer temperature, LOI, spring and summer precipitation	0.043	0.321	0.37	5.8
Spring Precipitation	None	0.064	0.315	0.088	6.4
	Summer temperature	0.062	0.431	0.068	6.9
	LOI	0.063	0.325	0.09	6.7
	Winter and summer precipitation	0.046	0.271	0.362	5.2
	Summer temperature, LOI, winter and summer precipitation	0.044	0.328	0.354	5.9
Summer Precipitation	None	0.048	0.208	0.312	4.8
	Summer temperature	0.056	0.344	0.142	6.2
	LOI	0.048	0.220	0.31	5.1
	Winter and summer precipitation	0.045	0.265	0.378	5.1
	Summer temperature, LOI, winter and spring precipitation	0.049	0.366	0.236	6.5

P = significance level of Monte Carlo permutation tests (499 unrestricted permutations)

6.10 SYNOPSIS

The chironomid stratigraphy is marked by notable shifts in community composition over the length of the core. The chironomid community change from zone 1 to zone 2 is characterised by a transition from eutrophic lake conditions to more oligotrophic conditions. This is evident by the increase in *Stempellina* and *Tanytarsus chinyensis*-type, which are associated with oligotrophic waters, and a decrease in taxa associated with agricultural activities, namely *Tanytarsus pallidicornis*-type, *Cladopelma*, *Procladius*, and *Polypedilum nubifer*-type. Taxa associated with semi-terrestrial and littoral environments, such as *Limnophyes/Paralimnophyes* and *Polypedilum sordens*-type, substantially increase at the beginning of zone 2 and LOI increases significantly, potentially indicating a significant event in the catchment. Historical evidence indicates that the lake was drained around this time (Woodmartin, 1886), Alleviation of farming activities around 1850 is likely to have taken place as a result of the large-scale shift in agriculture intensity caused by the Great Irish Famine of 1845-1849. This could have promoted a growth in the dominance of oligotrophic species and a decline in taxa associated with eutrophic lake conditions. Documentary evidence also shows the large-scale introduction of tree species into the area at this time (O'Rourke, 1889).

In zones 3 and 4, conditions become more eutrophic with an increase in taxa associated with mesotrophic-to-eutrophic conditions and a fall in taxa linked with less productive lake conditions. This is likely to be a result of increased farming activities in the late 19th century once socio-economic conditions improved after the Famine. Documentary evidence states that the lake was drained again in the early-1920s (Goodwillie *et al.*, 1992). At this time, lakes were drained for the reclamation of land for agricultural activities. An increase in the number and diversity of taxa associated with productive lakes and agricultural conditions is notable around this time. These taxa include *Tanytarsus pallidicornis*-type, *Cladopelma*, *Parakiefferiella bathophila*-type, *Procladius,* and *Polypedilum nubifer*-type along with lower levels of *Cricotopus cyclindraceus*-type, *Corynoneura edwardsi*-type, *Glyptotendipes pallens*-type, *Micropsectra junci*-type and *Endochironomus impar*-type. *Stempellina* declines in numbers throughout this zone, while *Stempellinella* (associated with mesotrophic lake states) becomes more abundant in the late 1950s until the 1970s. This peak in *Stempellinella* also mirrors an increase in taxa associated with agricultural activities. The increase in the abundance of taxa associated with more mesotrophic-to-eutrophic conditions in the 1950s corresponds with the introduction of a national-scale scheme that subsidised the cost of lime and fertilisers for Irish farmers (Irish Fertilisers Scheme 1945 – 1970). The use of fertilisers on agricultural land in the catchment of Lough Ballygawley is a potential cause for the shift to the more productive lake conditions evident in the chironomid stratigraphy. Shallower lake levels and more productive conditions seem to promote the increase of *Psectrocladius sordidellus/psilopterus*-type, which is linked with macrophytes. Finally, the expansion of forestry in the late 1940s, 1960s, 1990s and 2000s does not seem to have any significant impact on the chironomid community in the lake.

Despite the large-scale human impacts evident at this lowland lake, a temperature signal was still registered by the chironomid community. Redundancy analysis (RDA) provided evidence for the statistically significant influence of summer temperature on the chironomid community. Enhanced warming in the late 20th to early 21st centuries is evident in the chironomid-temperature reconstruction (Figure 6.13), with notable lower temperatures in the 1960s and in the late 19th century. Warming post-1980 is also evident in the RDA samples bi-plot (Figure 6.16). Temperature changes registered in the Markree summer temperature records closely track changes in the chironomid-temperature reconstruction over the late 19th to early 21st century, although the scale of change is muted. These results indicate that, despite human influence at this lake site, chironomids are shown to be sensitive to recent temperature change in Ireland. Nutrient enhancement throughout the 20th century is also a feature of this shallow lake. Recent research has suggested that climate warming on lake productivity may be co-linear. Recent research suggests the rising temperatures and longer growing seasons are enhancing nutrient loading in lakes through increased rates of mineralisation in catchment soils (Guo *et al*., 2013; Brookshire *et al*., 2011; Moss *et al*., 2011; Jeppesen *et al*., 2010; Rustad *et al*., 2001). Therefore, chironomid communities in shallow, productive lakes, such as Lough Ballygawley, could be responding to the combined influence of increased temperatures and nutrient loading.

The chironomid-inferred temperature reconstruction was extended beyond the scope of the ^{210}Pb-dated section of the core (Figure 6.14). This was carried out in order to determine temperature trends in the more distant past. However, the absence of an accurate dating model means that inferences with known climatic periods are only anecdotal. Taking the chironomid-inferred temperatures spanning ~1878 to 2009 as baseline climate conditions, a colder period is evident between 1866 and 1850, with a subsequent warmer period similar to present conditions between 1840 to 1760 (average of 14.7°C). The coldest temperatures in the record are inferred at 21 cm depth (ca. 1790) and may be indicative of cooler conditions in the Little Ice Age. As all inferred dates below the ^{210}Pb-dated portion of the core are based solely on estimated sedimentation rates and should only be regarded as an exploration of potential temperature patterns.

CHAPTER 7: LOUGH LUMMAN

7.1 LAKE BATHYMETRY

Lough Lumman has an ovate asymmetrical shape with elongated shelves on the northern and western sections (Figure 7.1). The lake reaches its maximum depth (2.7 m) at its centre. The profundal zone is narrow and long, stretching in a north-south direction; the sediment cores were taken within this sector. The transition from the deepest profundal area to the littoral zones is steepest on the eastern section of the lake with less severe slopes evident on the southern and southeastern sectors. In the northern and western areas a gentler slope dominates the profile. *Equisetum fluviatile* and *Carex rostrata* are evident in the littoral zone, while small amounts of *Scirpus* and *Nymphea alba* also exist. A narrow outflow channel (<0.2 m) is present in the northern section of the lake.

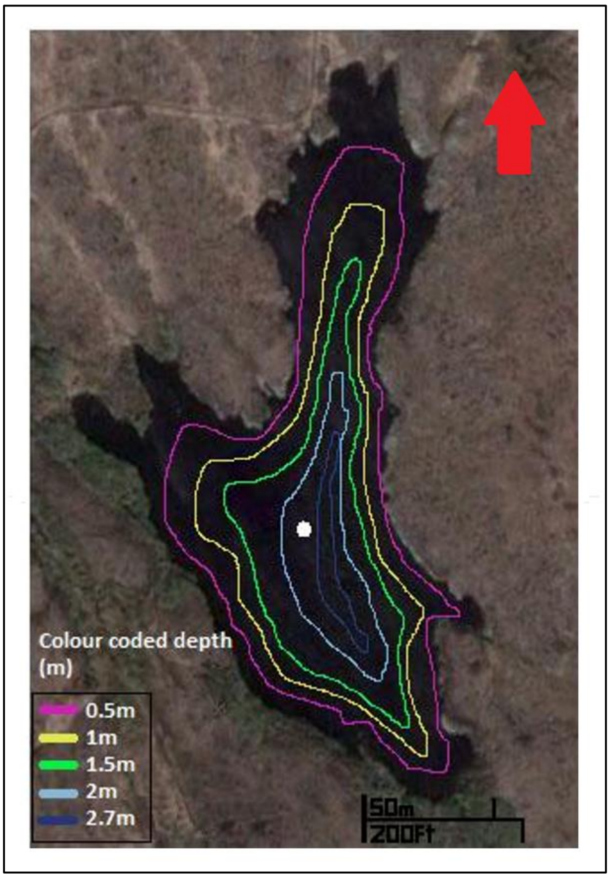


Figure 7.1 Bathymetric map of Lough Lumman. White circle marks point where sediment cores were extracted.

7.2 LAKE SEDIMENT CHARACTERISTICS AND LOI

Duplicate cores were recovered from the centre of Lough Lumman. Both sediment cores were uniform in appearance, consisting of dark brown gyttja. The first core was 41 cm in length, while the second was 39 cm long. The longer core was designated the master core and its sediment was used for radiometric dating, LOI and chironomid extraction. LOI from this core is presented in Figure 7.2. Similar to Lough Meenagraun and Lough Ballygawley, LOI results will be discussed in terms of organic carbon (550˚C) as the inorganic carbon (950˚C) remains consistently low and stable over the length of the sediment core. Organic carbon values range from 46% to 75% throughout the core. The lowest values are concentrated in the deepest section of the core. There is a notable increase to 26 cm depth (75%), which represents the peak LOI in the core. A drop in values occurs hereafter until a depth of ~22 cm, when values stabilise at ~58%. An increase in organic carbon takes place from 15 cm to 9 cm, reaching an average level of 66%. A final gradual decline organic carbon values takes place between 9 cm and 6 cm, before stabilising until present day values of 63%.

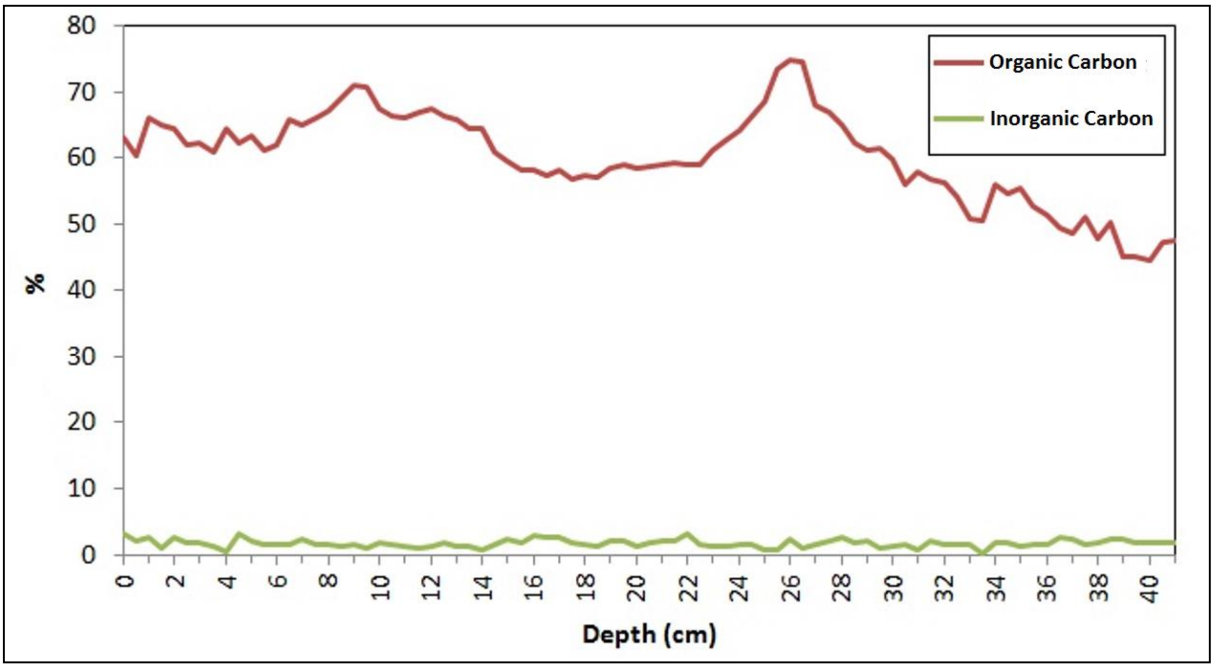


Figure 7.2 Organic and inorganic content for the entire sediment core of Lough Lumman.

7.3 DATING MODEL

7.3.1 ^{210}Pb Chronology

The top 8.5 cm section of core A was datable by ^{210}Pb and represents 1893 to 2009. The results of the ^{210}Pb age depth model are displayed in Figure 7.3.

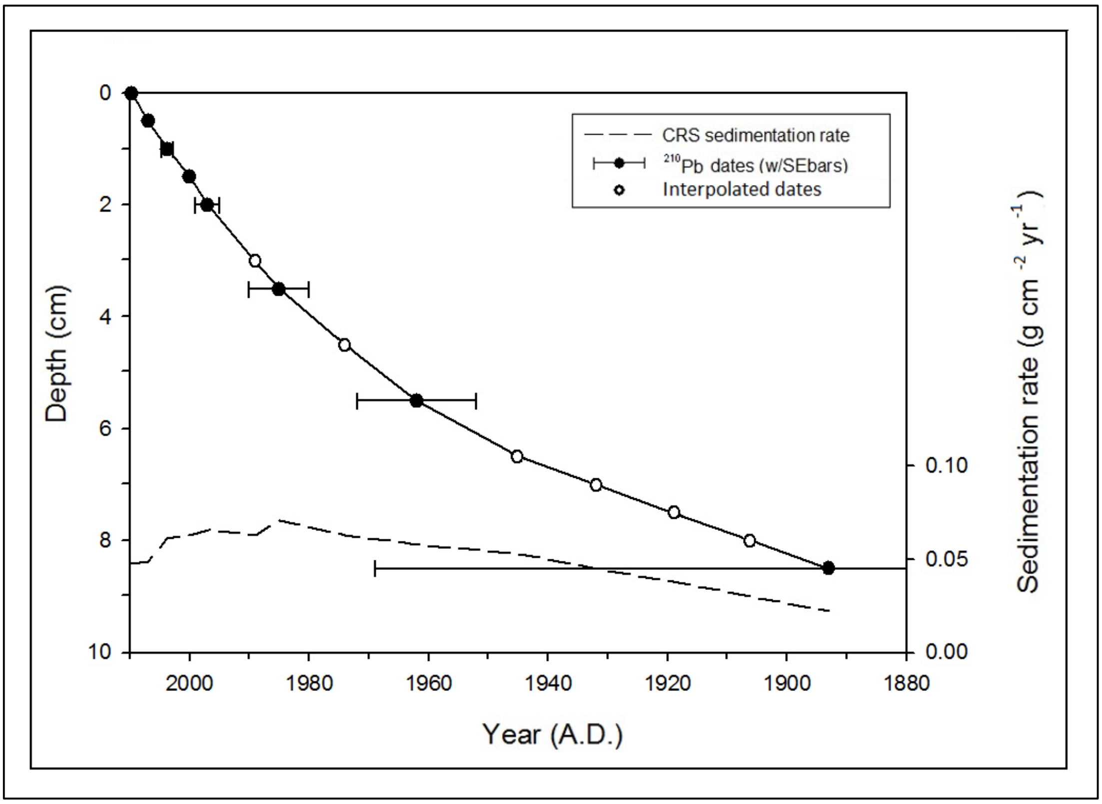


Figure 7.3 ^{210}Pb age-depth model Lough Lumman utilising the CRS (constant rate of supply) model.

Standard errors (SE) of ^{210}Pb dates ranged from 76 years at the bottom of the chronology to approaching zero error at the top of the core. SE of ^{210}Pb dates at 1960 were 17 years (due to 1 cm interval used for dating the sediment layers 5.5 cm and 6.5 cm depth). After 1985, SE reduced to between 4 years and approaching 0 years towards the top of the core. The mean dry mass accumulation rate (DMAR) varied between 1893 and 2009. From 1900 until 1954 the lake experienced a DMAR of 0.045 g $cm^{-2}yr^{-1}$ (22 yr cm^{-1}). DMAR increased between 1954 and 1977 to 0.083 g $cm^{-2}yr^{-1}$ (12 yr cm^{-1}), before a further notable increase of 0.18 g $cm^{-2}yr^{-1}$ (5.5 yr cm^{-1}) between 1977 and 1987. The most recent portion of the sediment core displays a slight decline in DMAR to 0.16 g $cm^{-2}yr^{-1}$ (6 yr cm^{-1}) from the late 1980s to present.

Overall, the ^{210}Pb chronology exhibits no significant re-deposition, indicating that no slumps have occurred at the modern water-surface interface where the core was recovered.

7.3.2 ^{14}C Dating Problems

Two AMS radiocarbon dates of humic acid fraction from bulk sediment were obtained for Lough Lumman. A sample for ^{14}C dating was taken from the bottom of the core and another was taken just below the ^{210}Pb-dated section. The sample taken from the middle section of the core (19 cm to 19.5 cm) was found to be older than the sample from the bottom section of the core (40.5 to 41 cm). As with Lough Meenagraun, the lake is bordered by bog and it is likely that already-decaying bog material from the surrounding catchment is entering the lake. This, in turn, contaminates in-lake sediment layers by reworking older material through newer sediments (Watson *et al*., 2010), essentially distorting the levels of ^{14}C (Shore *et al*., 1995). Subsequently, ^{14}C dates were deemed unreliable and were not used for further analysis.

7.4 TEMPERATURE DATA LOGGERS

Air temperature was collected at one hour intervals from October 2009 to October 2011. Hourly water temperature data were collected for August 2010 until October 2011. Water temperature data between October 2009 and July 2010 was not recorded due to equipment malfunction, which was not detected until July 2010. Mean daily temperatures were calculated from the average of the 24 hour readings. It was found that daily mean air and water temperatures follow similar rates of warming and cooling over the recordings from August 2010 until October 2011 (Figure 7.4), with maximum mean values for both air and water temperature reached in June, July and August. As with Lough Ballygawley, water temperature registers higher mean summer temperatures than air temperature.

Daily mean air temperatures recorded by the data loggers, between April 2010 and September 2010, follow similar rates of warming and cooling with the mean daily maximum, minimum and mean Markree temperature record over the same period (Figure 7.5).

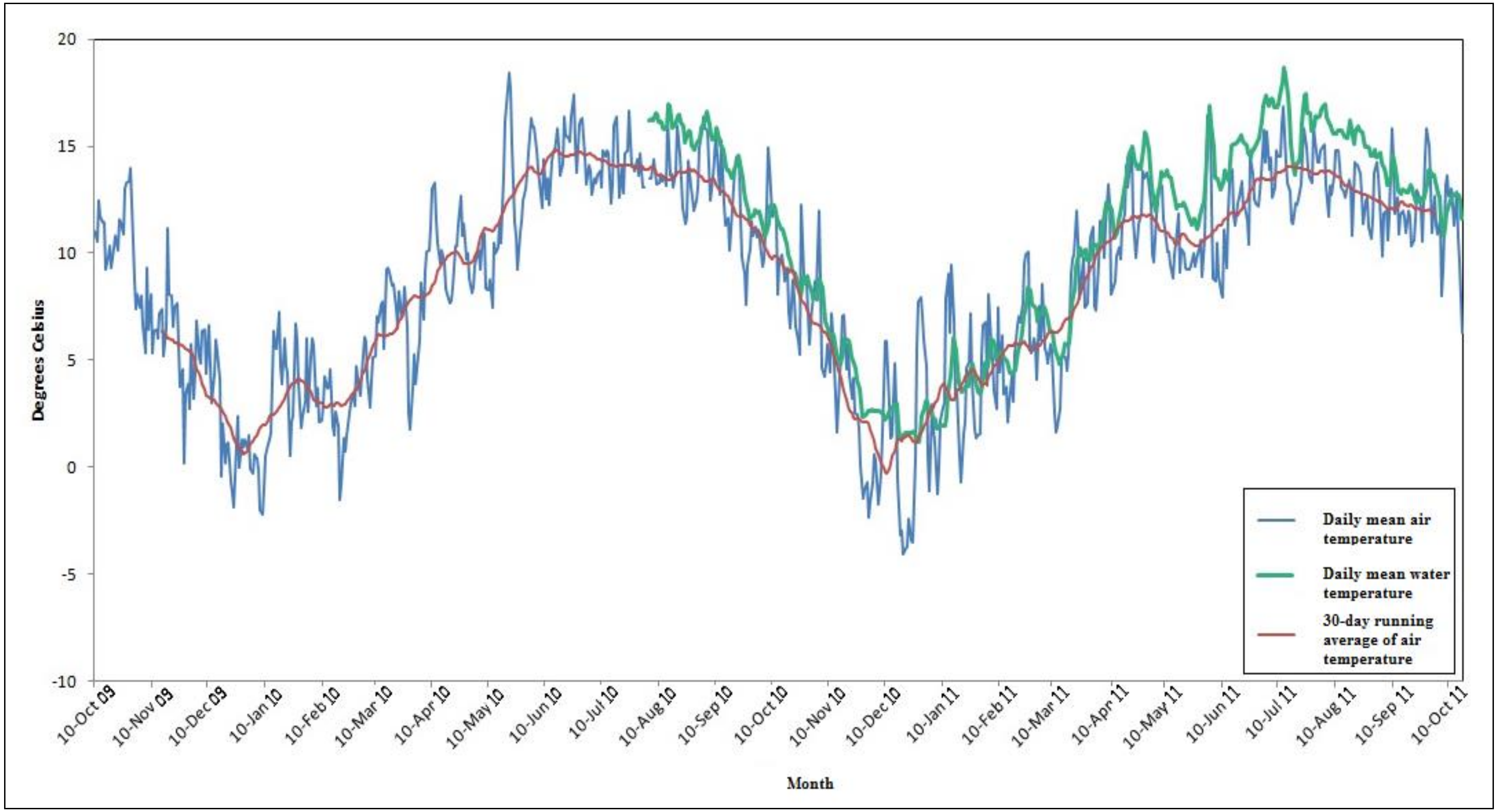


Figure 7.4 Mean daily air temperatures, calculated from the average of the 24 hour readings over the entire recording period of two years, collected using an air temperature data logger.

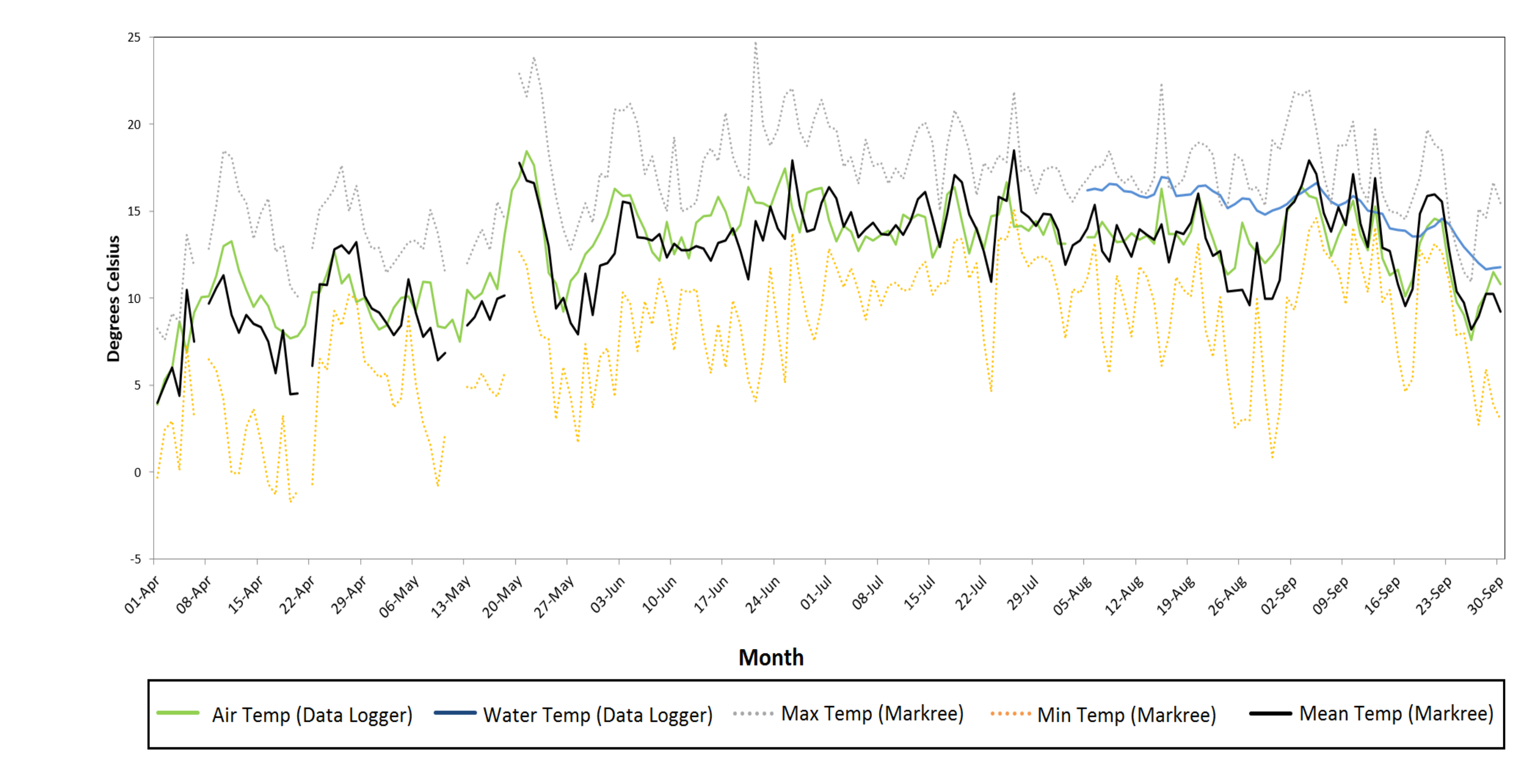


Figure 7.5 Daily mean air temperatures recorded from April 2010 to September 2010 compared with the daily maximum, minimum and mean temperatures from the Markree record for the same period.

Water temperature spanning August 2010 to September 2011 follows a similar pattern, albeit with more muted daily fluctuations and extremes. Mean daily air temperature collected using the data logger was slightly lower (~0.576ºC between April-September 2010) than the mean daily air temperature at Markree Observatory. Lough Lumman (172 m a.s.l.) is 146 m higher than the Markree site (26 m a.s.l.). Local lapse rates as calculated using Goodale *et al*. (1998) (0.0074°C m^{-1} elevation), suggest Lough Lumman temperature should be 1.08˚C cooler than Markree Observatory temperatures. As there were few trees within the Lough Lumman catchment to provide adequate shading, it is possible that some exposure to direct sunlight could account for this difference.

7.5 CHIRONOMID COMMUNITY COMPOSITION

Chironomid community change from Lough Lumman will be reported firstly for the entire core and secondly from the ^{210}Pb-dated section, which covers the top 8 cm (16 samples) of the core. The dated portion of the stratigraphy extends to 1893, and can thus be compared with the Markree Observatory temperature record. In total, 42 taxa were identified from the full master core (Figure 7.6), with an average of 19 taxa per sample. Twelve taxa were deemed rare through the master core, with 21 identified as rare in the ^{210}Pb-dated section. Over the course of the core, head capsule concentrations varied between 31.5 head capsules ml^{-1} and 196 capsules ml^{-1}, and was highest in the lower half of the core (Figure 7.6). A minimum of 50 head capsules were enumerated for every sample, with an average of 86 head capsules per sample. The Shannon-Wiener Diversity Index ranged greatly between 1.8 and 3.3 over the full core. Mean taxa diversity in each of the three zones only varied between 2.5 and 2.6, indicating that the taxa diversity is more variable between samples than across zones. Interestingly, diversity seems to have a negative relationship with head capsule concentrations. The chironomid chronology has been divided into a three zones. None of these zones were found to be significant using the BSTICK model (Bennett, 1996), but are used here to aid interpretation.

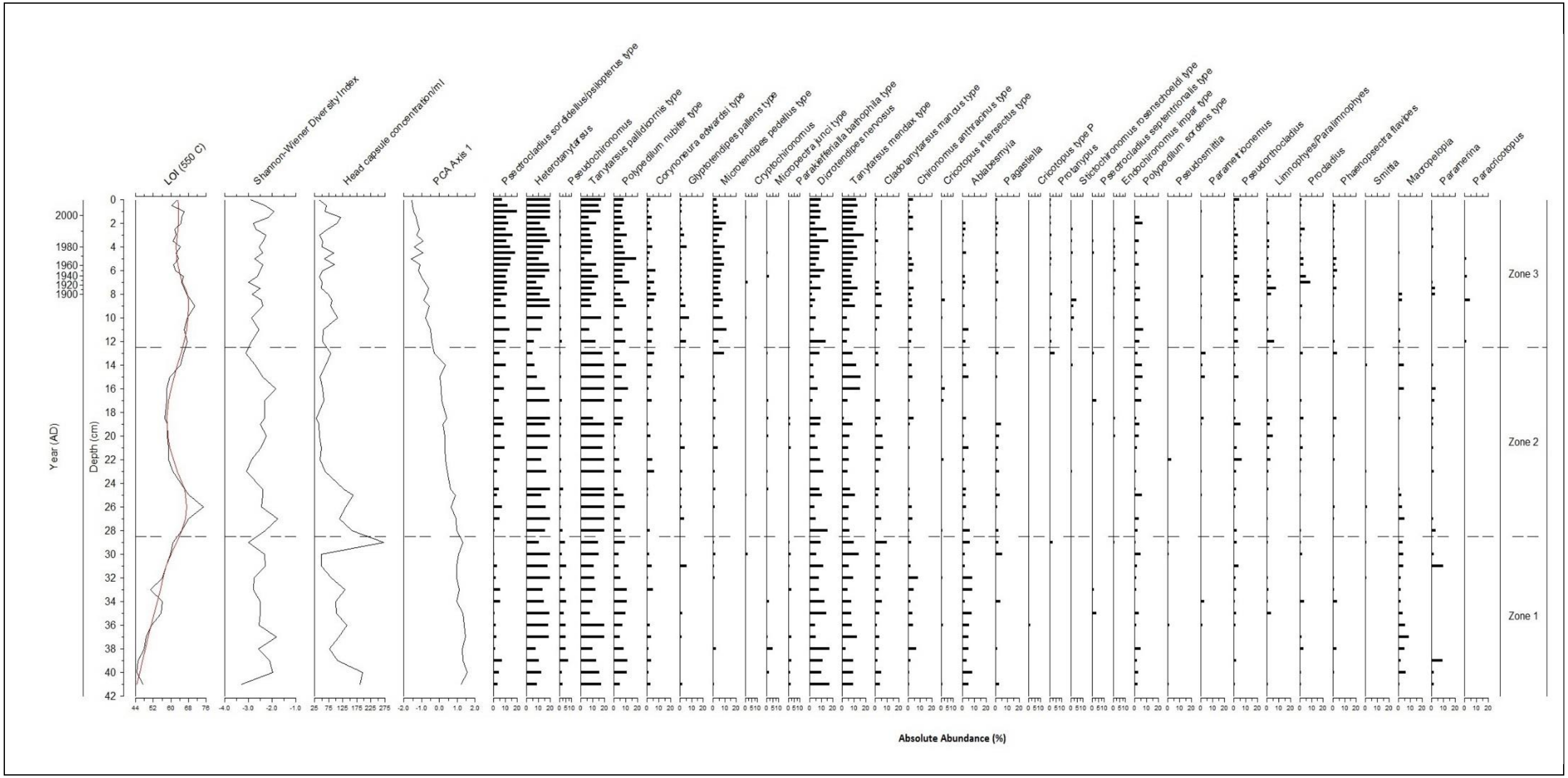


Figure 7.6 Chironomid stratigraphy of important taxa and community zonation for Lough Lumman. LOI (550˚C), Shannon-Wiener Diversity of each sample, Axis 1 scores from Principal Component Analysis (PCA) of chironomid data, and summer air temperatures inferred using Potito (forthcoming) transfer function with LOESS smoother (span = 0.2).

7.5.1 Zone 1 (41 cm – 29 cm)

This zone contains the highest percentages of warm water taxa (34%). These taxa include *Dicrotendipes nervosus*-type (11%), *Tanytarsus mendax*-type (9%), *Ablabesmyia* (5.5%), *Cladotanytarsus mancus*-type (4%), *Chironomus antracinus*-type (3%) and *Pagastiella* (1.5%). Taxa associated with cooler, less productive lake conditions, such as *Protanypus*, *Cricotopus*-type *P*, and *Psectrocladius septentrionalis*-type are present in this zone at lower levels of ~1%. Acidophilic taxa in this zone include *Heterotanytarsus* (9%) and *Psectrocladius sordidellus/psilopterus*-type (4%). Taxa associated with eutrophic lake conditions are abundant in zone 1, reaching levels of 31% of the total chironomid community. The main taxa associated with these conditions are *Polypedilum nubifer*-type (8%), *Tanytarsus pallidicornis*-type (15%), *Corynoneura edwardsi*-type (3%), *Polypedilum sordens*-type (2%) and *Procladius* (2%). *Procladius* reaches its maximum abundance in this zone at 38-37 cm, and again at 34 cm, which coincides with the peak in taxa associated with terrestrial/semi-terrestrial environments. Terrestrial/semi-terrestrial include *Limnophyes/Paralimnophyes*, *Smittia*, *Pseudosmittia*, and *Pseudorthocladius* and *Parametriocnemus*. Finally, head capsule concentrations are greatest in zone 1 at 124 capsules ml^{-1} of sediment. Organic carbon increases throughout this zone from 48% to 61%.

7.5.2 Zone 2 (28 cm – 13 cm)

Zone 2 is dominated by taxa associated with eutrophic lake conditions, comprising 37% of the chironomid community in the zone. *Tanytarsus pallidicornis*-type (23%) is the most dominant species in this category, while *Corynoneura edwardsi*-type is present in lower numbers but shows an increase throughout this zone. *Heterotanytarsus*, a humic water taxon, is prominent, although it decreases in abundance towards the end of the zone (32% to 11%).

Taxa indicative of warmer water conditions comprise 24% of the chironomid community in zone 2. These include *Tanytarsus mendax*-type, which displays a general increase throughout the zone, while *Cladotanytarsus mancus*-type, *Pagastiella* and *Dicrotendipes nervosus*-type reach their highest values between 18 cm and 25 cm depth. Taxa linked with cooler, more oligotrophic conditions decrease in percentages in zone 2. *Cricotopus* type *P* and *Krenopelopia* are absent from this zone, while *Protanypus* is only present in a single sample at 13 cm. Taxa associated with warm, productive conditions and taxa linked with cooler, less productive conditions reach their maximum values in this zone at around the same time, indicating that the chironomid community is likely not responding to temperature change but to other environmental pressures.

Taxa associated with terrestrial/semi-terrestrial environments such as *Limnophyes/Paralimnophyes*, *Metriocnemus*, *Macropeloia*, *Pseudorthocladius* and *Parametriocnemus*, show an increase in zone 2 (6%). These taxa reach their highest levels between 22 cm and 18.5 cm. The abundance of *Phaenopsectra*, which is linked with macrophytes, follows a similar trend to taxa associated with semi-terrestrial/terrestrial environments, which may indicate fluctuations in lake level. *Procladius* as already mentioned, is associated with the eutrophic lake conditions and appears to, once more, broadly follow the trajectory of terrestrial/semi-terrestrial taxa. Finally, organic content increases in the earliest section of zone 2, reaching its highest level of 75% at 26 cm, before decreasing to 60% for the rest of the zone. Head capsule concentration decreases overall to 79 head capsules ml^{-1}. Shannon-Wiener Diversity Index values remains similar to zone 1 at 2.5.

7.5.3 Zone 3 (12 cm – 0 cm)

Zone 3 is characterised by an overall increase in acidophilic taxa, which comprise a third of the chironomid community. *Heterotanytarsus* shows an increase throughout this zone from levels of 6% to 21%. Taxa associated with eutrophic conditions are still abundant, but fall to an overall level of 31%. These taxa show a general decline throughout this zone, most notably *Glyptotendipes pallens*-type and *Polypedilum sorden*-type (~5% to 0%). *Tanytarsus pallidicornis*-type closely follows the trajectory of *Heterotanytarsus*, indicating the close link between changes in nutrient enrichment and brown water conditions. Taxa associated with warmer waters also increase throughout zone 3. The taxa accounting for most of this change is *Tanytarsus mendax*-type, which makes-up ~10% of the taxa in this zone. Taxa linked with cooler, less productive lake conditions, such as *Stictochironomus rosenschoeldi*-type, *Pseudochironomus* and *Protanypus*, decrease throughout this zone.

Terrestrial/semi-terrestrial taxa fall to 4.5%. *Limnophyes/Paralimnophyes*, *Pseudochironomus* and *Parametriocnemus* all show a decrease throughout zone 3.

The highest concentrations occur at the start of this zone, however other taxa associated with terrestrial/semi-terrestrial environments, such as *Metriocnemus*, *Pseudosmittia* and *Smittia*, are absent. Taxa associated with terrestrial/semi terrestrial environments and *Procladius* continue to follow similar patterns of change throughout the zone. Organic content of the sediment decreases in this zone. Head capsule concentrations further decrease to 69 head capsules ml^{-1} of wet sediment. Shannon-Wiener Diversity Index values increase slightly to 2.6 in zone 3.

7.5.4 Community Compositional Change

The transition from zone 1 to zone 3 can be seen as a shift to the left along PCA Axis 1 ($\lambda = 0.321$) (Figure 7.7). This shift can be explained by a transition towards more acidic, eutrophic lake conditions, as these taxa are found on the left of the species bi-plot (Figure 7.8). The shift along PCA Axis 2 ($\lambda = 0.075$) in the bi-plot is likely driven by alterations in the dominance of taxa associated with the semi-terrestrial/terrestrial margins (Figure 7.8). Samples to the top of the bi-plot (Figure 7.7) are comprised of *Procladius* (eutrophic) and *Limnophyes/Paralimnophyes* (terrestrial/semi-terrestrial), while samples to the bottom of the bi-plot have less of these taxa. Samples to the top of the bi-plot also contain a high abundance of *Phaenopsectra,* which is associated with macrophytes (Pinder and Reiss, 1983). Therefore, PCA Axis 2 ($\lambda = 0.075$) could be indicative of lake level status. As the volume of water in the lake decreases, the level of water along the shelves of the lake and their margins will also decrease and the semi-terrestrial habitat would likely increase. Also, the exposed shelves, shallower water conditions and expanded photic zone should lead to a more productive lake.

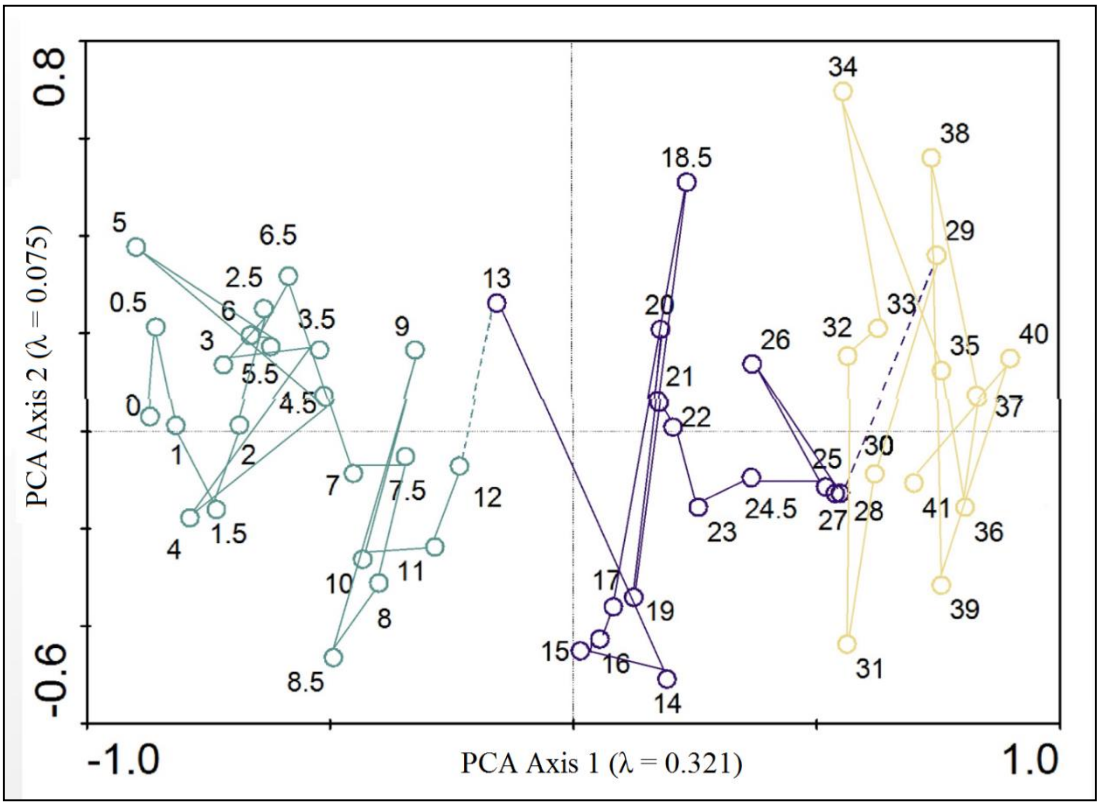
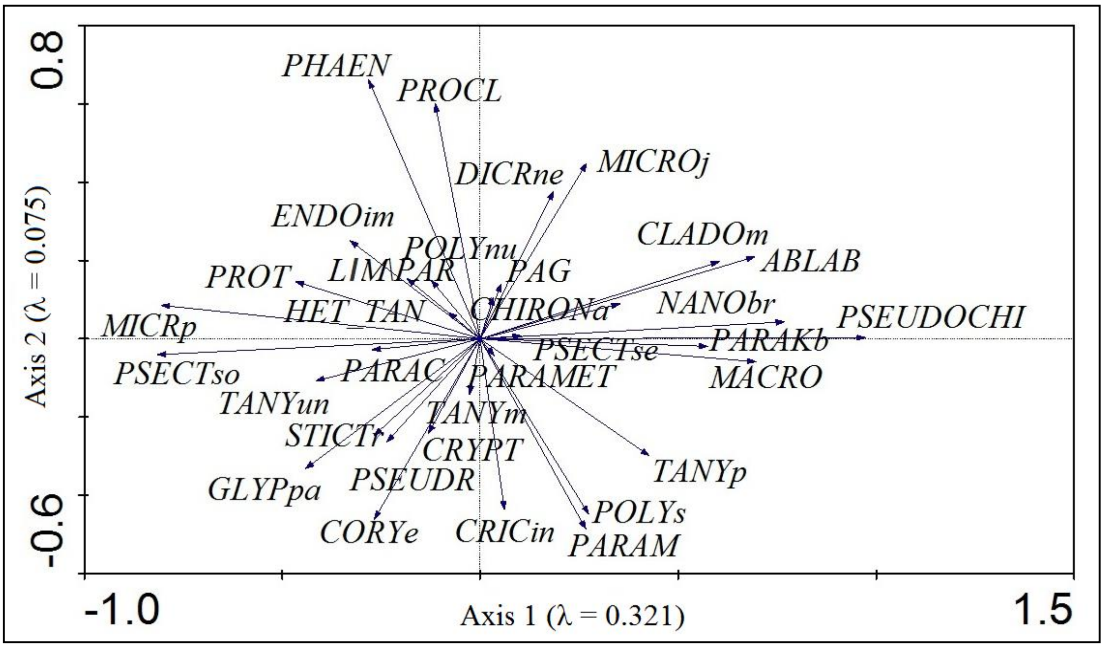


Figure 7.7 Principal component analysis (PCA) bi-plot for chironomid samples displaying changes in chironomid trajectory (chironomid zones are highlighted in different colours on this graph). Circles indicate different depths (cm).



Legend

Code name	Taxa full name	Code name	Taxa full name
ABLAB	*Ablabesmyia*	PARAKb	*Parakieferiella bathophila*- type
CHIROa	*Chironomus anthracinus*- type	PARAM	*Paramerina*
CLADOm	*Cladotanytarsus mancus*- type	PARAMET	*Parametriocnemus*
CORYe	*Corynoneura edwardsi*- type	PHAEN	*Phaenopsectra*
CRICin	*Cricotopus intersectus*- type	POLYnu	*Polypedilum nubifer*- type
CRYPT	*Cryptochironomus*	POLYsor	*Polypedilum sordens*- type
DICRne	*Dicrotendipes nervosus*- type	PROCL	*Procladius*
ENDim	*Endochironomus impar*- type	PROT	*Protanypus*
GLYPpa	*Glyptotendipes pallens*- type	PSECTse	*Psectrocladius septentrionalis*- type
HET_TAN	*Heterotanytarsus*	PSECTso	*Psectrocladius sordidellus/psiloperus*- type
LIM\PAR	*Limnophyes/Paralimnophyes*	PSEUDOR	*Pseudorthocladius*
MACRO	*Macropelopia*	PSEUDOS	*Pseudosmittia*
MICROj	*Micropsectra junci-type*	PSEUDOCI	*Pseudochironomus*
MICRp	*Microtendipes pedellus-type*	STICTr	*Stictochironomus rosenschoeldi*- type
NANOba	*Nanocladius balticus*- type	TANYm	*Tanytarsus mendax* -type
PAG	*Pagastiella*	TANYp	*Tanytarsus pallidicornis*- type
PARAC	*Paracricotopus*	TANYun	*Tanytarsus* undiffrenciated

Figure 7.8 PCA bi-plot of common chironomid taxa.

7.6 CLIMATE AND LAKE VARIABLES THROUGH TIME

Detailed examination of the ^{210}Pb-dated portion of the chironomid stratigraphy was carried out in order to gauge the impacts of known environmental change on the chironomid community through time. PCA Axis 1 scores and the chironomid-inferred temperature (C-IT) reconstruction were compared with the Markree summer temperature, seasonal precipitation and the NAO record in order to identify if temperature and precipitation are having an influence on the chironomid community trajectory over this record (Figure 7.9).

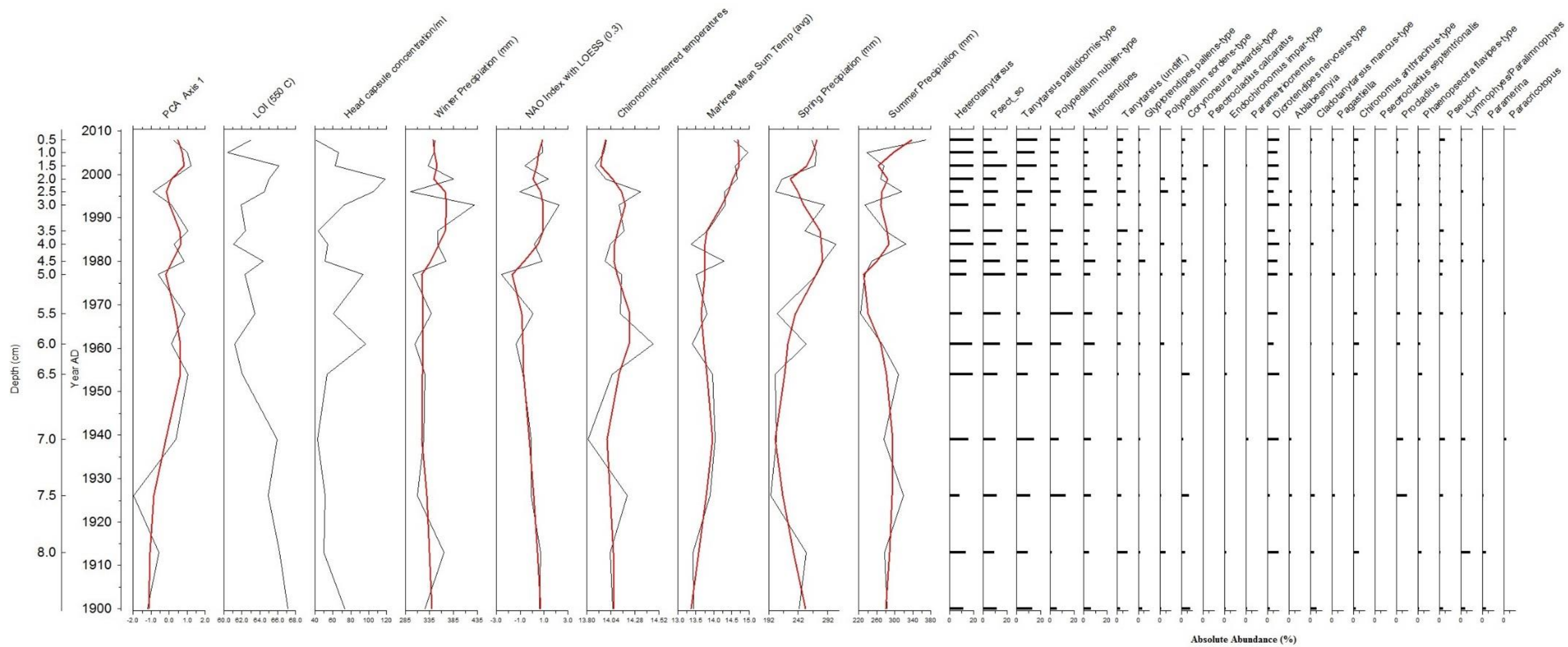


Figure 7.9 Chironomid-based summer air temperature reconstruction ,chironomid PCA, LOI, CRS of Lough Lumman and Markree summer temperature, seasonal precipitation and NAO index (with LOESS smoother with a span of 0.3).

This portion of the sediment core is dated to 1900 (between 8 cm to the top of the core). C-IT, NAO index values, Markree summer temperature and winter, spring and summer precipitation data were all placed on the same timeline by averaging the variables over each dated sediment interval. As the ^{210}Pb-dated samples are spaced further apart downcore, they essentially cover longer periods of time (11-17 years vs. 1-4 years at the top of the core), and finer-scale variations in climate may be lost in these larger time frames in the lower section of the core. DMAR and Shannon-Wiener Diversity Index were excluded from the graph as the data was relatively consistent over this section of the core and revealed no important environmental information.

Figure 7.9 shows that the C-IT reconstruction does not follow the Markree summer temperature record. This suggests that the chironomid community in Lough Lumman is not responding to changes in temperature through time, but is being influenced by other environmental pressures. Qualitative examination of taxa associated with both warm and cold conditions in line with the Markree summer temperature record reveals no evident connections. Furthermore, the chironomid temperature model appears to be more synchronous with head capsule concentrations. Winter precipitation appears to have a negative relationship with head capsule concentrations through the core; as winter precipitation increases, head capsule concentration decreases. This suggests that winter precipitation is having an impact on this lake, possibly influencing the chironomid community.

An increase in winter/spring precipitation appears to correspond with a decrease in taxa linked with terrestrial/semi-terrestrial environments, for example *Limnophyes/Paralimnophyes* and *Pseudorthocladius.* Taxa linked with these environments are abundant between 1900 and 1940 and from 1970 until 2009, with notable decreases in abundance in 1960s, 1993 and 1999. This decline coincides with years in which winter precipitation was notably high. Maximum values of these taxa are reached in years with low precipitation.

7.6.1 Chironomid Compositions Change – ^{210}Pb-Dated Portion of the Core

The PCA samples bi-plot for the dated portion of the core shows a general movement across Axis 1 ($\lambda = 0.183$) from 1900 to 2008 (Figure 7.10). Samples that span the late 19th to early 20th century contain a high abundance of *Microtendipes* *pedellus*-type (associated with eutrophic lakes, as identified from the Irish training set), *Polypedilum sordens*-type (associated with eutrophic lake conditions, and also associated with macrophytes), *Corynoneura edwardsi*-type (linked with eutrophic lake conditions) and *Limnophyes/Paralimnophyes* (associated with terrestrial/semi-terrestrial environments). Samples in this section of the bi-plot show the coupling of *Limnophyes/Paralimnophyes* with taxa associated with eutrophic lakes. All of these taxa show the strong relationship to PCA Axis 1 ($\lambda = 0.183$) (Figure 7.11). As samples move from the right of the bi-plot to the left hand side across PCA Axis 1($\lambda = 0.183$), the lake appears to become more acidic, due to a higher abundance of *Heterotanytarsus* and *Psectrocladius sordidellus/psilopterus*-type (acidophilic taxa).

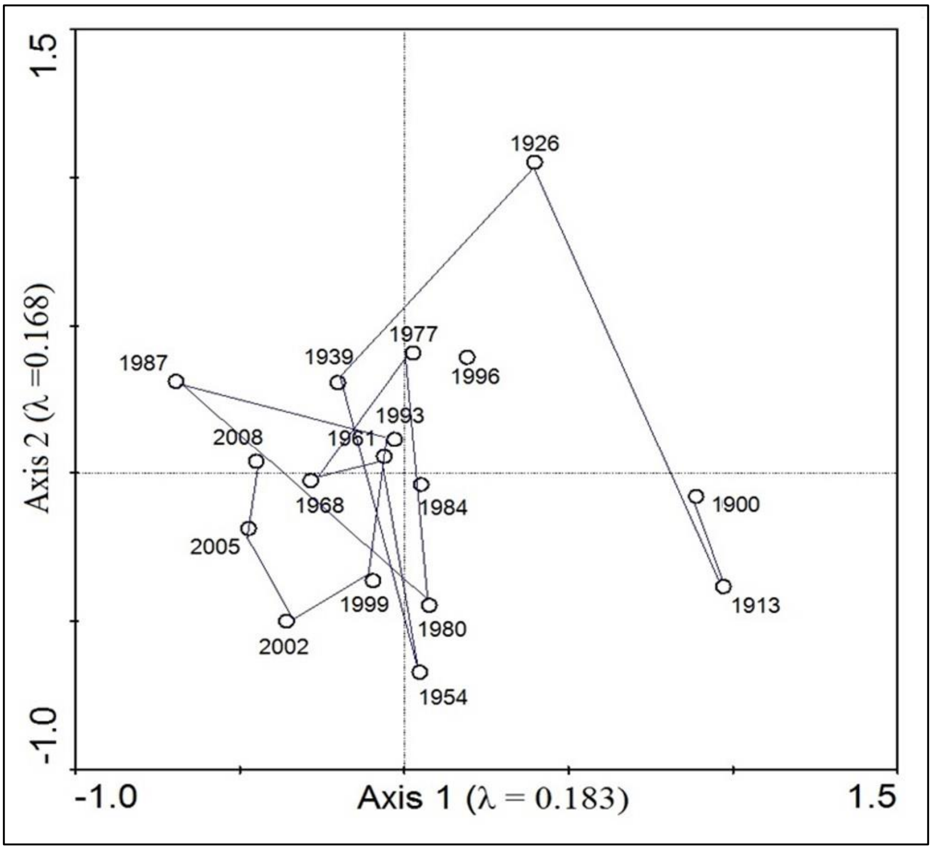


Figure 7.10 Time-trend principal component analysis (PCA) bi-plot chironomid samples displaying changes in chironomid trajectory over the ^{210}Pb-dated section of the core. Zones are not highlighted in different colours, as no zones were significant.

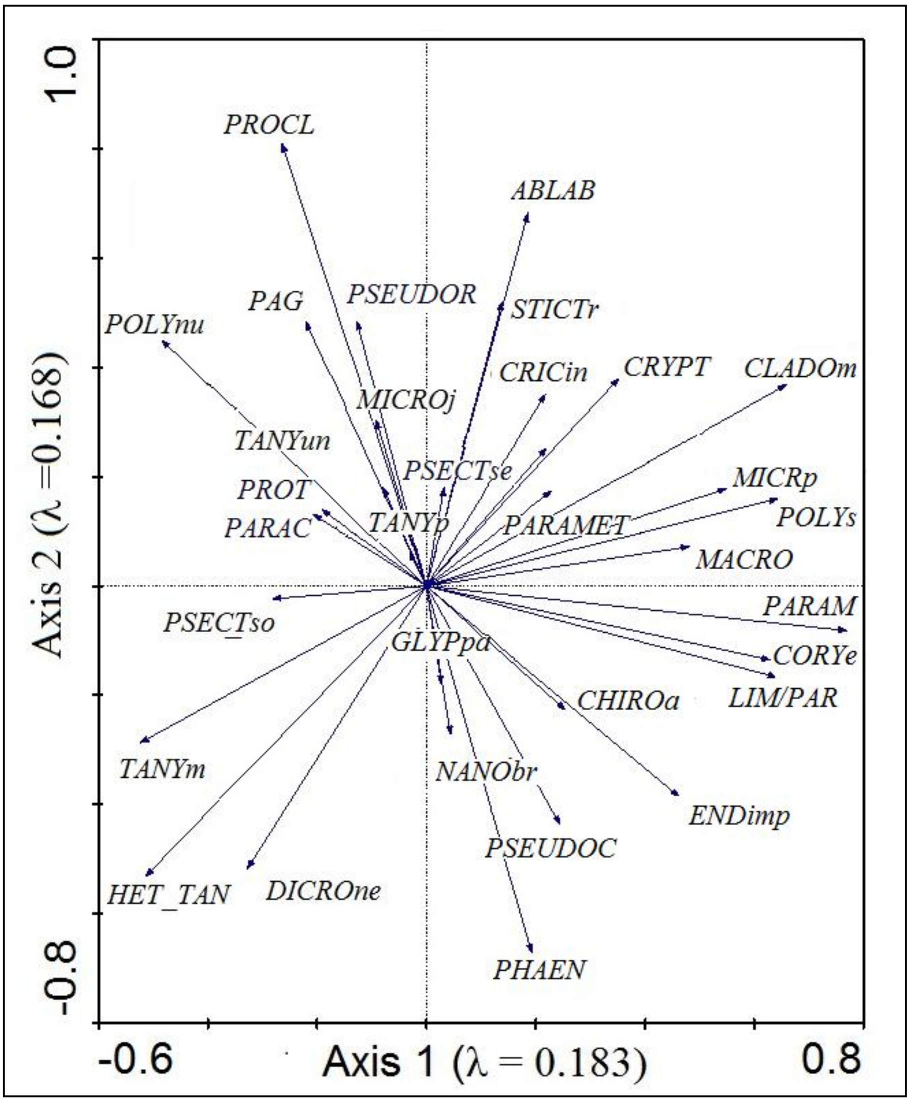


Figure 7.11 PCA bi-plot of common chironomid taxa from the ^{210}Pb-dated section of the sediment core. Refer to legend from previous.

7.7 REDUNDANCY ANALYSIS – RDA

Following similar lines of enquiry to Lough Meenagraun and Lough Ballygawley, redundancy analysis (RDA) was carried out on samples from 1900 to 2008. The five variables selected were summer temperature, LOI, and precipitation values for winter, spring and summer. The five variables selected explain 27% of the chironomid community variance, with RDA Axis 1 explaining 11.6% and Axis 2 explaining 6.9% (Table 7.1).

Table 7.1 Redundancy analysis (RDA) utilised linear responses showing eigenvalues species environmental correlations, cumulative percentage variance in species data, canonical coefficients and T-tests.

	Axis 1	Axis 2	Axis 3	Axis 4
Full model				
Eigenvalue	0.116	0.069	0.054	0.032
Species-envt. Corr.	0.831	0.764	0.890	0.605
Cum.% var. Spp.	11.6	18.5	23.8	27
Canonical coefficients				
Summer air temp	0.407	0.335	0.231	-0.360
LOI	-0.672	-0.039	-0.067	-0.297
Winter precipitation	0.039	0.697	-2.934	0.100
Spring precipitation	-0.012	0.492	0.352	0.198
Summer precipitation	-0.128	-0.187	0.542	0.198
Significant T-values				
Summer air temp	1.726	1.380	0.920	-1.496
LOI	-3.521**	-0.151	-0.262	-1.207
Winter precipitation	0.151	3.765**	-1.188	0.399
Spring precipitation	-0.047*	2.189*	1.457	0.785*
Summer precipitation	-0.501	-0.740*	2.503*	0.943

**P < 0.01, *P < 0.05

Species-envt. Corr. = species environment correlation for each axis

Cum.% var. Spp. = cumulative percent variance in species data

LOI displays the strongest relationship with RDA Axis 1, while spring precipitation shows a moderate relationship (Table 7.1). Winter precipitation shows the strongest relationship with RDA Axis 2 while spring precipitation shows a less substantial, but still evident, relationship with this Axis (Table 7.1). Samples that are located towards the bottom of the sample bi-plot generally span the early to mid-20th century and contain a higher abundance of *Limnophyes/Paralimnophyes* (linked with terrestrial/semi-terrestrial environments), *Procladius* (associated with eutrophic lake conditions), *Polypedilum sordens*-type (associated with macrophytes) and *Polypedilum nubifer*-type (associated with eutrophic lake conditions). These taxa are negatively related to winter and spring precipitation, likely indicating that lower precipiation in these seasons results in lower lake water levels, creating a large semi-terrestrial/terrestrial habitat along the lake margins and exposing a large photic zone and more productive in-lake condtions. A further examination of the species bi-plot shows that *Limnophyes/Paralimnophyes* (linked with terrestrial/semi-terrestrial environments) displays a strong relationship with RDA Axis 1 (Figure 7.12), suggesting that this taxon is associated with higher levels of organic carbon. Samples which contain a higher abundance of *Limnophyes/Paralimnophyes* span the early 20^{th} century (Figure 7.13).

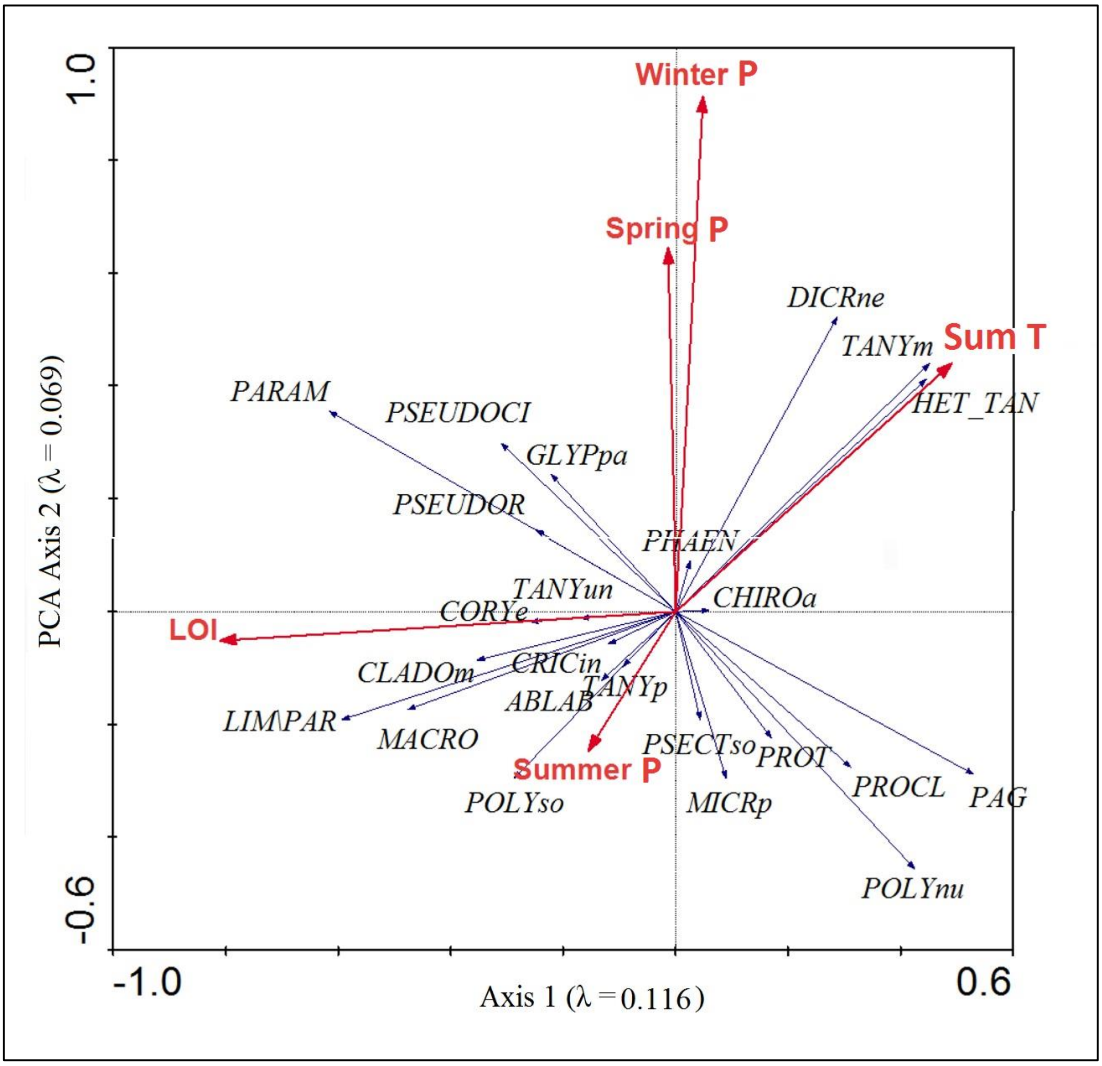


Figure 7.12 RDA bi-plot showing species distribution being influenced by LOI, summer temperature (Sum T), winter precipitation (Winter P), spring precipitation (Spring P), summer precipitation (Sum P).

Samples that are clustered within the upper right quartile in the sample bi-plot, span the late 20th to early 21st century and seem to be responding to higher levels of winter and spring precipitation, along with higher summer temperatures. These samples contain a higher abundance of *Tanytarsus mendax*-type, *Heterotanytarsus* and *Dicrotendipes nervosus*-type. These taxa suggest warmer and more acidic lake conditions in the more recent samples. Higher precipitation levels are likely causing bog material from the catchment to be washed into the lake, thus creating more humic water conditions where *Heterotanytarsus* thrives. *Tanytarsus mendax*-type is a thermophilic taxon and closely follows summer temperature, indicating that summer temperature may still be having an influence on the chironomid community, but to a lesser extent than LOI, winter and spring precipitation.

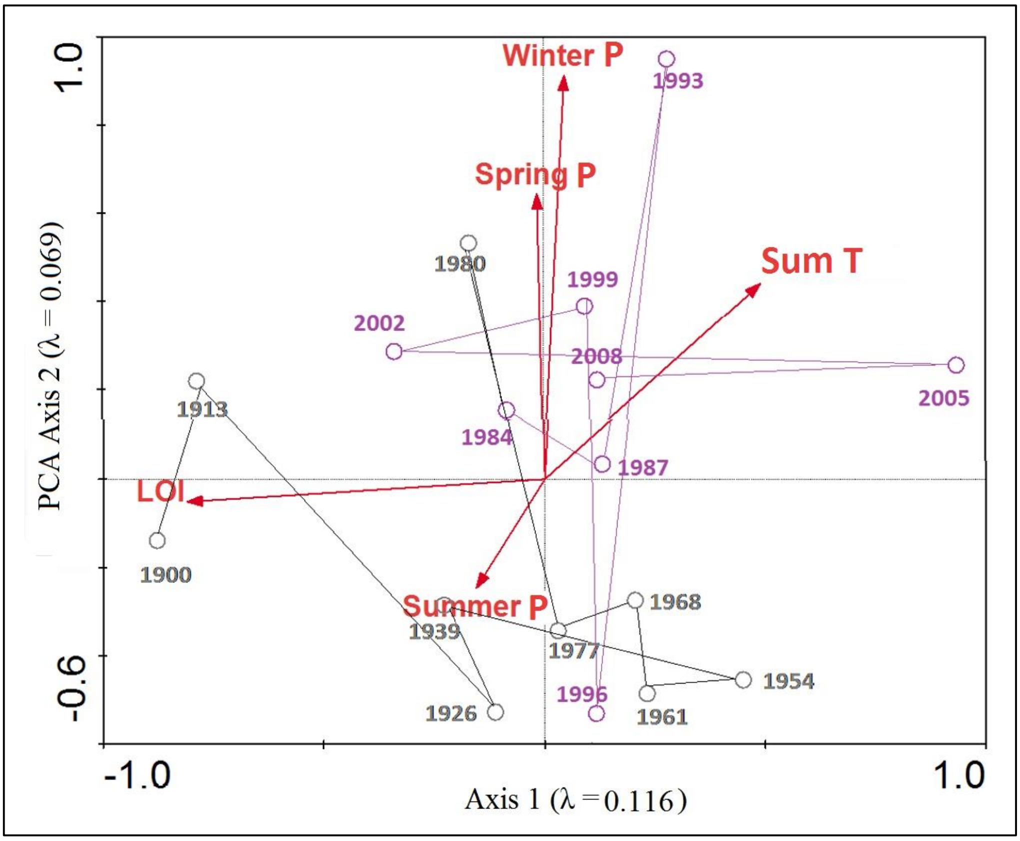


Figure 7.13 RDA bi-plot showing sample distribution being influenced by LOI, summer temperature (Sum T), winter precipitation (Winter P), spring precipitation (Spring P), summer precipitation (Sum P).

Partial RDAs further demonstrate that LOI and winter precipitation are having the greatest influence on chironomid community trajectory, explaining 8.6% and 6.5% respectively (Table 7.2). Although P-values show that the five environmental variables are not significant, the data highlights which of the variables are having the greatest influence on chironomid trajectory. Overall, LOI exhibits the greatest control over species distribution since 1900, followed by winter precipitation. When the other variables were partialled out, both summer air temperature and summer precipitation became marginally stronger (7.2 % and 4.9% respectively). LOI becomes stronger once summer precipitation is factored out (9%) and stronger still when seasonal precipitation minus autumn is partialled out (11.5%). Furthermore, LOI becomes strongest once seasonal precipitation and summer temperature are factored out (11.7%), while winter precipitation becomes strongest once LOI is factored out. This emphasises the important control organic carbon has on the chironomid trajectory of Lough Lumman. The presence of prominent shelves in the lake subjects the lake to hydromorphological pressures, where fluctuations in water level will alter the size of photic zones and the size of semi-terrestrial/terrestrial habitats. A decline in lake level will likely create a larger semi-terrestrial habitat for chironomid communities, along with an increase in the photic zone. This would increase lake productivity, resulting in higher levels of organic carbon.

Table 7.2 Partial RDA for each environmental variable.

Variable	Covariable	λ1	λ1/λ2	P	% variance
Summer Air Temperature	None	0.060	0.314	0.498	6
	LOI	0.058	0.316	0.502	6.3
	Seasonal precipitation	0.060	0.331	0.552	7
	LOI, seasonal precipitation	0.055	0.325	0.588	7.2
LOI	None	0.086	0.462	0.122	8.6
	Sum temp	0.084	0.459	0.136	9
	Seasonal precipitation	0.099	0.585	0.092	11.5
	Summer temperature, seasonal precipitation	0.093	0.550	0.150	11.7
Winter Precipitation	None	0.065	0.333	0.39	6.5
	Summer temperature	0.061	0.335	0.494	6.5
	LOI	0.065	0.377	0.402	7.1
	Spring and summer precipitation	0.051	0.260	0.664	5.6
	Summer temperature, LOI, spring and summer precipitation	0.048	0.284	0.704	6.4
Spring Precipitation	None	0.049	0.251	0.726	4.9
	Summer temperature	0.049	0.260	0.722	5.3
	LOI	0.610	0.346	0.432	6.7
	Winter and summer precipitation	0.040	0.209	0.834	4.5
	Summer temperature, LOI, winter and summer precipitation	0.520	0.307	0.656	6.8
Summer Precipitation	None	0.042	0.216	0.854	4.2
	Summer temperature	0.041	0.214	0.850	4.4
	LOI	0.041	0.224	0.842	4.4
	Winter and summer precipitation	0.038	0.198	0.858	4.2
	Summer temperature, LOI, winter and spring precipitation	0.036	0.213	0.862	4.9

P = significance level of Monte Carlo permutation tests (499 unrestricted permutations)

7.8 SYNOPSIS

Lough Lumman is characterised by a gradual change in the chironomid community through time. The lake appears to become progressively more acidic throughout the core, with the increase in taxa associated with humic waters (*Heterotanytarsus*) and acidic conditions (*Psectrocladius sordidellus/psilopterus*-type). No evidence of human influence upon Lough Lumman and its catchment was found in documentary sources or in field investigations. This indicates that, at least over the length of the ^{210}Pb-dated section, the chironomid community is being driven by natural environmental or local catchment-driven processes.

Superimposed on this broader-scale change in the chironomid community, were notable sub-decadal to decadal fluctuations. From a detailed investigation into chironomid community change with various climate variables and environmental variables, it is evident that changes in lake level are largely responsible for these small-scale fluctuations. As mentioned at the start of this chapter, Lough Lumman has notable long shallow shelves along its northern and western margins. Chironomid community change compared with meteorological recordings since 1900 indicates that these shelves may be flooded during years in which winter/spring precipitation is high. In turn, when precipitation is low, lake level likely falls. Years when winter/spring precipitation was low, taxa associated with both terrestrial/semi-terrestrial and eutrophic lake conditions increased. This likely indicates that when the water level in the lake drops as a result of reduced winter/spring precipitation, the depth of water on these long shelves also drops, creating ideal habitat for taxa associated with terrestrial/semi-terrestrial areas, expanding the lake photic zone and increasing lake productivity. Therefore, an increase in *Limnophyes/Paralimnophyes* along with *Procladius* provides evidence for chironomid response to these changing hydromorphological lake conditions.

Furthermore, changes in winter precipitation is driven by changes in the NAO; when the NAO is in a positive phase winter precipitation increases and when the NAO is in a negative phase winter precipitation decreases. RDA data provides further evidence for the implication of winter precipitation influencing the chironomid trajectory. However, organic carbon remains the most important controlling variable on chironomid community change. Organic carbon is likely influenced by the water level in Lough Lumman at times when the water level is lower, the photic zone increases and macrophytes are likely to become more dominant along the lake margins where water depth is now reduced. This creates more organic material in the lake and hence more organic carbon.

In terms of the ability to capture summer temperature change in Lough Lumman with chironomids, it appears that communities are responding to lake level changes more readily than to temperature. This is largely due to lake morphology, where the presence of long shelves being flooded intermittently will alter the ecological functioning of the lake. Consequently, the C-IT reconstruction is not accurately representing temperature change through time. Rather, the chironomid-temperature reconstruction is following a synchronous trend with head capsules concentrations.

The evidence from this lake suggests that semi-terrestrial/terrestrial species may be useful as a proxy for lake level.

CHAPTER 8: LOUGH NAKEEROGE

8.1 DATING MODEL

8.1.1 Core re-alignment

During the analysis of Lough Nakeeroge, uncertainties in core recovery were identified from an evaluation of the ^{14}C dating model, LOI analysis and chironomid community change throughout the two extracted cores. The master core was created from two overlapping cores, core A and core B, based on LOI (550˚C) correspondence between core segments. Duplication in chironomid community composition was evident between depths of 258 cm and 274 cm (core B segment of master core) and 288 cm and 296 cm (core A segment of master core). This was initially thought to be a two-pronged environmental event. However, radiocarbon dates appeared to be older in the core B segment of the master core than core A. Therefore, the possibility of realigning the cores was explored. This involved moving core B by aligning LOI (550˚C) between core segments in line with correcting the duplication in chironomid community structure. It was found that if the entire core B sediment sequence was moved down 42 cm and the bottom section of core A (280-349 cm) was shifted down 13 cm, LOI (550˚C) collation between core A and core B segments improved greatly, ^{14}C dating model presents an almost linear accumulation rate. Figure 8.1 illustrates which sections of the master core are composed of core A and core B sediments before and after this calibration. Furthermore, the duplication in chironomid community becomes synchronously (Figure 8.2).

Moving core B down 42 cm extended the master core to a depth of 401 cm. The top section of the master core, between 50 cm to 240 cm, consisted of sediment from core A. Despite a gap in the core, between 143 cm and 149 cm, it was decided to use core A due to uncertainties surrounding the exact alignment of the top segment of core B. Subsequently, the top section of core B, between 142 cm to 238 cm, was not used in the master core and the ^{14}C date at 126.5 cm was discarded. The master core was composed of sediment from core B between 244 cm to 320 cm, and again between 365 cm and 401 cm; sediment from core A was again used between 293 cm and 365 cm. An overlap between core A and core B is evident between 292 cm and 320 cm in the master core.

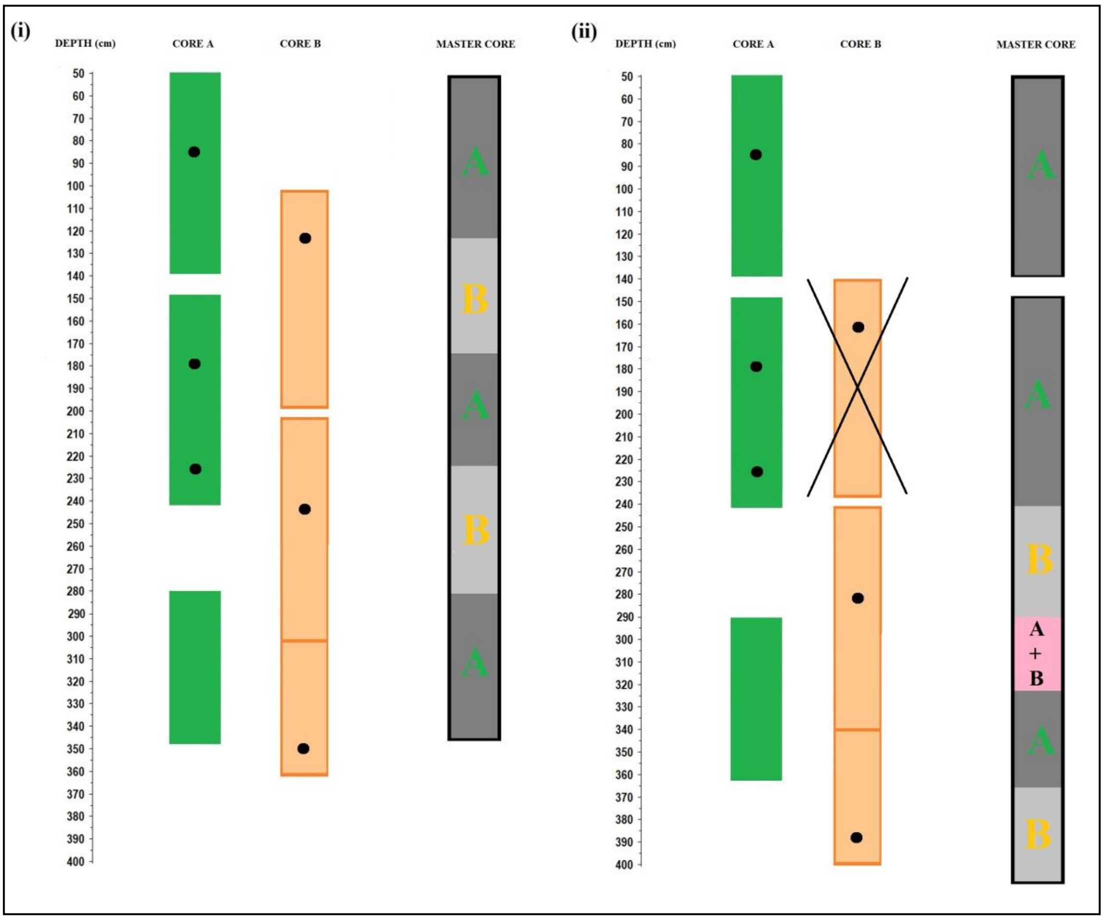


Figure 8.1 (i) Core A and core B before calibration. (ii) Core A and core B after the entire core B was moved down 42 cm and the bottom segment of core A was moved down 13 cm. Black dots indicate the levels and the cores from which ^{14}C dates were obtained. Corresponding master cores are also shown to indicate which sections of are composed of core A and core B. The pink section in the (ii) master core marks the area where chironomid duplication was corrected and the overlap can be visually seen in the Lough Nakeeroge chironomid stratigraphy.

Figure 8.2 shows the overlap in the chironomid community from 292 cm to 320 cm in the master core. Chironomid taxa correspond well in the re-aligned cores, with the most obvious correspondence from *Lauterborniella* (corresponding depths show the only instances of this taxa in either core), *Psectrocladius septentrionalis*-type, *Tanytarsus chinyensis*-type and *Heterotrissocladius marcidus*-type.

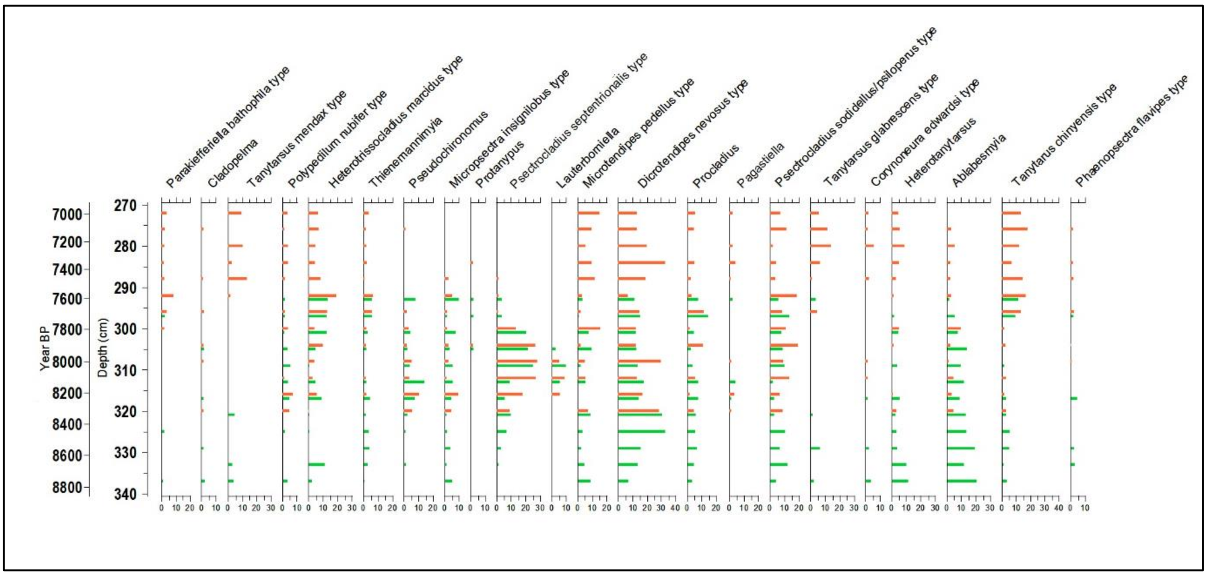


Figure 8.2 Chironomid stratigraphy from 270 cm to 340 cm showing corrected duplication in important taxa from core re-alignment. Orange colour signifies core B, while green colour signifies core A.

8.1.2 Age-Depth Model

The ^{14}C age-depth model before (Figure 8.3 (i)) the core calibration demonstrates the evident problems in the original core alignment. Figure 8.3 (ii) illustrates how the ^{14}C dating model improved after the cores were moved. The bulk sediment date at the top of core B was discarded, as the date as this depth was too old and did not follow with the other dates. All remaining core segments were either radiocarbon dated, or were aligned via chironomid community overlap. The results of the age-depth model evident in Figure 8.3 (ii), show that sedimentation rates throughout the dated levels of the master core maintain a relatively consistent pattern. At bottom of the core, between 10,146 cal. yr BP and 7,465 cal. yr BP (390 cm to 288 cm), the sedimentation rate was modelled at 0.038 cm yr^{-1} (26.29 yr cm^{-1}). Between 7,445 cal. yr BP and 5,542 cal. yr BP (287 cm to 224 cm) the sedimentation declines slightly to 0.033 cm yr^{-1} (30.22 yr cm^{-1}), before increasing to 0.035 cm yr^{-1} (28.41 yr cm^{-1}) for the period spanning 5,513 cal. yr BP to 4,395 cal. yr BP (223 cm to180 cm). Towards the top of the core, between 4,273 cal. yr BP and 1,474 cal. yr BP (179 cm and 50 cm) the sedimentation rate increases to 0.045 cm yr^{-1} (21.78 yr cm^{-1}). The sedimentation rate exhibits no significant irregularities between the dated sections of the master core.

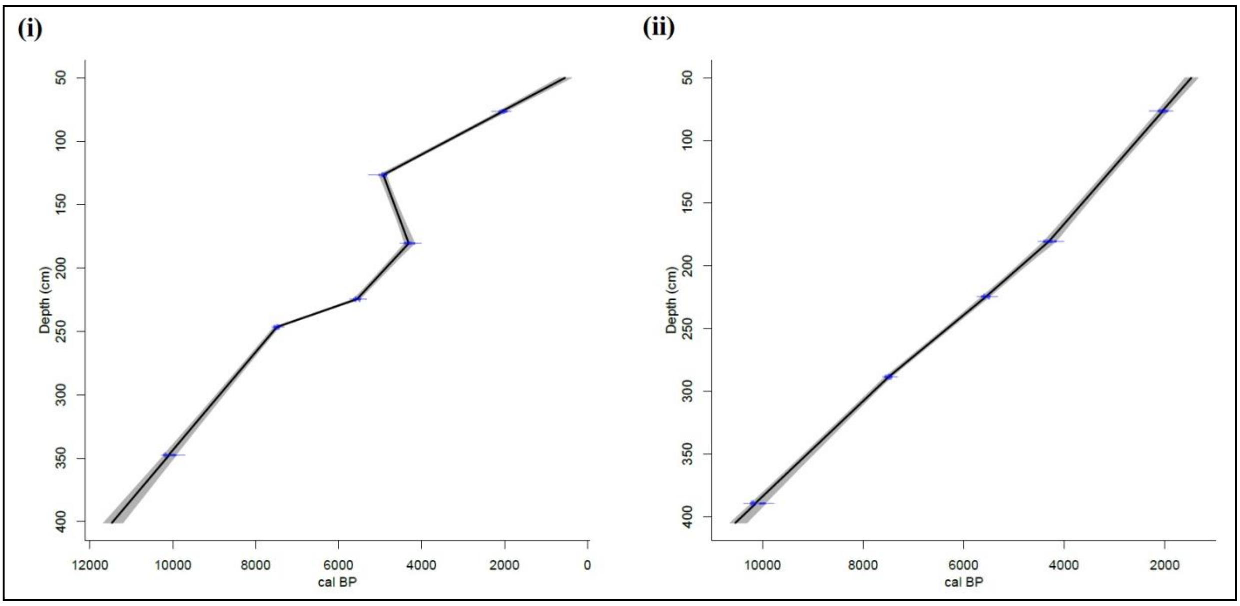


Figure 8.3 Age-depth models (i) before calibration with all six ^{14}C dates, (ii) after calibration with five ^{14}C dates (the radiocarbon date from the top of the core B sequence was omitted as this core B segment was not used in the master core).

8.2 LOSS-ON-IGNITION (LOI)

LOI results will be discussed solely in terms of organic carbon (550˚C) as inorganic carbon (950˚C) does not yield any significant trends. Organic carbon values from both cores are presented in Figure 8.4. This graph also illustrates the alignment between core A and core B. The depths that were used for chironomid analysis are marked on the graph to illustrate that most of the prominent peaks and troughs in organic carbon are represented in the final analysis. Organic carbon values ranged from 3.2% to 43.9% over the length of both cores.

The greatest levels of organic carbon occurred between 6,600 cal. yr BP and 4,300 cal. yr BP, while the lowest values were concentrated in the deepest section of the core, between 10,350 cal. yr BP to 10,200 cal. yr BP. At 10,100 cal. yr BP an increase in organic carbon takes place and stagnates at ~17% until 8,450 cal. yr BP. Hereafter, a prominent increase in organic carbon takes place with values reaching

~28%, which lasts until 8,350 cal. yr BP. A fall in LOI values, to an average of ~16%, is notable in both cores between 8,000 cal. yr BP and 7,600 cal. yr BP. A subsequent increase in LOI takes place, where values of 35% are reached at 6,650 cal. yr BP. Finally, organic carbon fluctuates between 25% and 35% for the remainder of the core, with notable troughs between 3,860 cal. yr BP and 3,770 cal. yr BP and, again, between 1,700 cal. yr BP and 1,650 cal. yr BP.

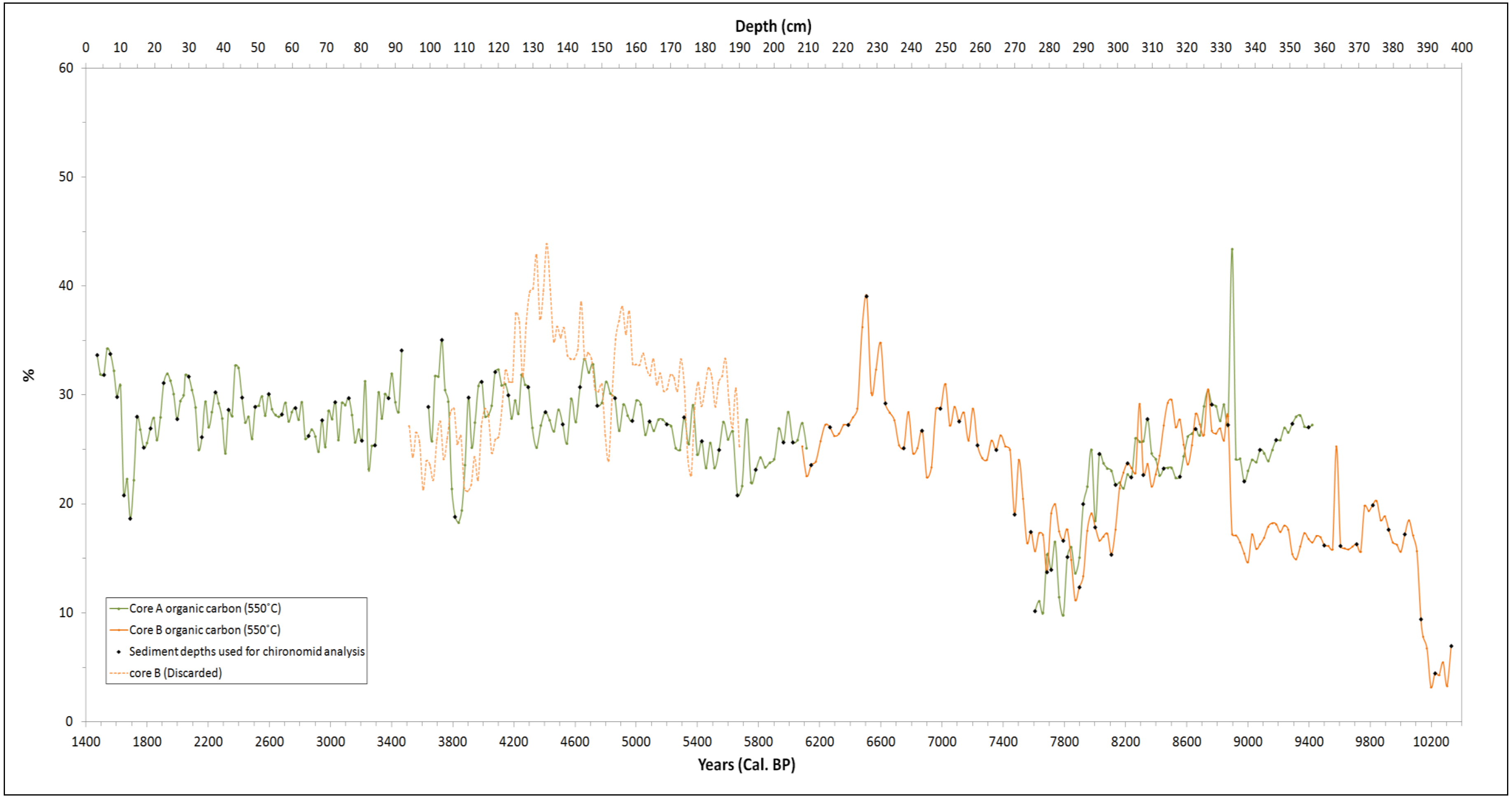


Figure 8.4 Organic Carbon (550˚C) for core A and core B sediment sequences for Lough Nakeeroge. Black dots indicate the sediment levels that were used for chironomid analysis. Orange dashed line indicates the segment of core B that was discarded from the master core.

8.3 CHIRONOMID COMMUNITY COMPOSITION

A stratigraphic diagram of the common chironomid taxa is displayed in Figure 8.5. The chronology was divided into five statistically significant zones. There were 54 taxa identified in Lough Nakeeroge, with 36 common taxa. There was an average of 17 different taxa per sample, with a minimum of 7 taxa in the two samples from the bottom of the core (10,350 to 10,200 cal. yr BP), and a maximum of 25 taxa at 8,765 cal. yr BP. The lowest average of the number of taxa per sample occurs in zone 1, while the highest level is found in zone 2. The Shannon-Wiener diversity index ranged from 0.5 to 2.0, with the lowest levels evident at the bottom of the core (10,400 cal. yr BP) and the highest diversity at the top of the core (1,560 cal. yr BP). Head capsule concentrations ranged from 10 to 127 head capsules ml^{-1} of wet sediment, with head capsules more densely concentrated in the bottom two samples of the core. Organic carbon (550˚C) is very low in these two samples, and pollen analysis[4], which is ongoing on the sediment core, identified a high concentration of pollen in these two samples. This is likely due to lower sedimentation rates in this portion of the core, which is beyond the ^{14}C dating model. Finally, diversity and head capsule concentration seem to follow a similar trend until 3,400 cal. yr BP, where this relationship breaks down

8.3.1 Zone 1 (10,350 – 10,200 cal. yr BP)

Zone 1 is marked by the lowest values of organic content (550˚C), chironomid head capsule and pollen grain concentrations. The zone is also characterised by the highest concentrations of cool water taxa in the Lough Nakeeroge record. *Micropsectra insignilobus*-type (64%), *Tanytarsus lugens*-type (8%), *Tanytarsus chinyensis*-type (8%) and *Protanypus* (4%) comprise 84% of the taxa in this zone. There are also several thermophilous taxa present, such as *Microtendipes pedellus*-type (3%), *Polypedilum nubifer*-type (3%) and *Cladopelma* (2%), albeit in low numbers. This zone displays the coldest chironomid-inferred summer temperatures (C-IT), with lowest temperature in the bottom two samples.

[4] Pollen analysis is being carried out by Prof. Chris Caseldine, University of Exeter, UK.

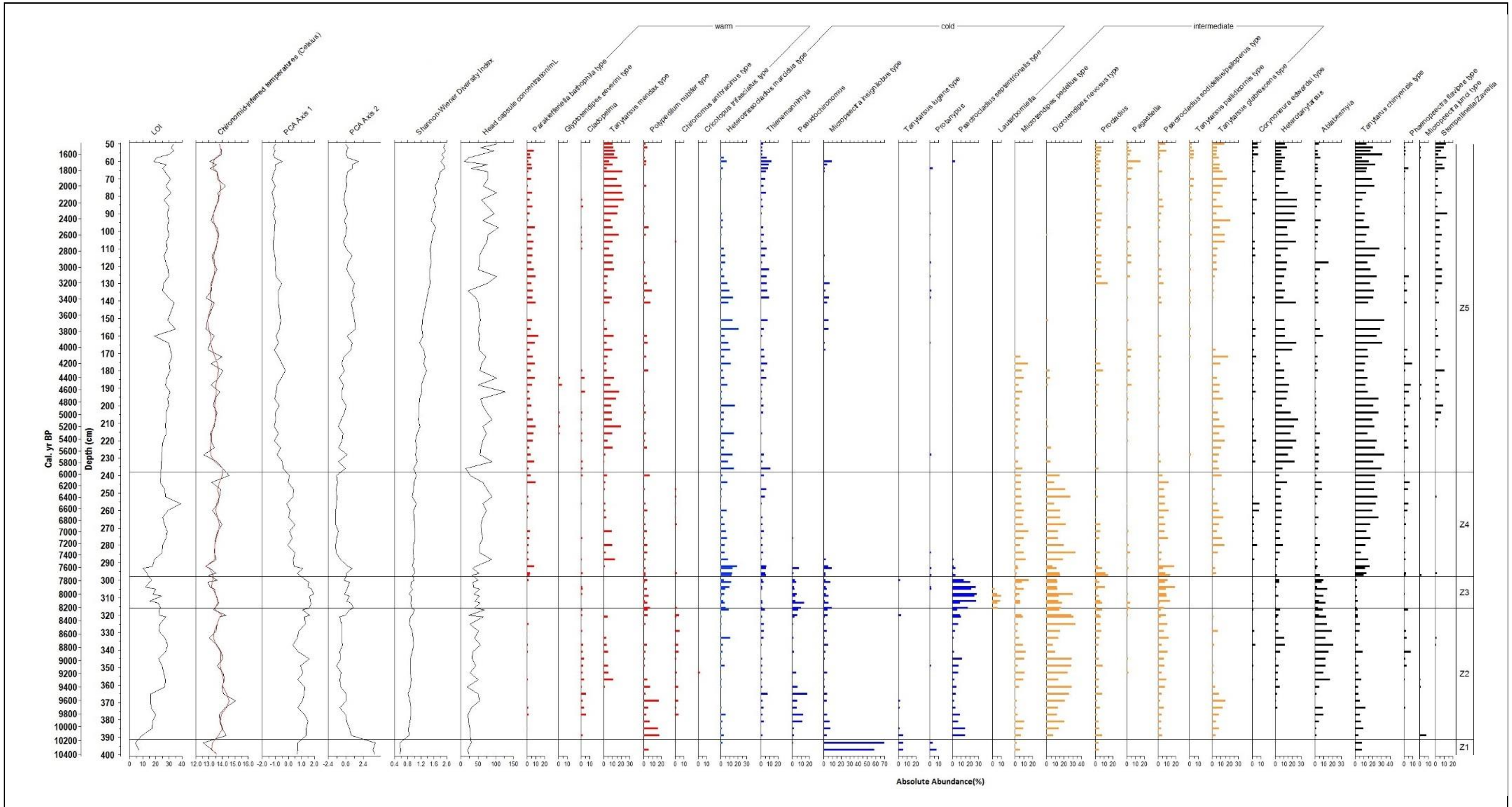


Figure 8.5 Chironomid stratigraphy of important chironomid taxa and community zonation. LOI (550˚C), Shannon-Wiener Diversity of each sample, chironomid head-capsule concentrations, Axis 1 and Axis 2scores from Principal Component Analysis (PCA) of chironomid data, and summer air temperatures inferred using Potito *et al.* (forthcoming) transfer function with LOESS smoother (span =0.1).

These samples are estimated at 10,350 cal. yr BP to 10,200 cal. yr BP in the dating model. However, they lie below the last radiocarbon date in the inorganic portion of the core, and likely pre-date this estimated age. Head capsule concentrations are low in zone 1 with an average of 25 head capsules ml^{-1}, and diversity is also low at 0.56.

8.3.2 Zone 2 (10,200 – 8,250 cal. yr BP)

Zone 2 is characterised by a rise in taxa associated with warmer, more productive lake conditions, such as *Microtendipes pedellus*-type (6%), *Psectrocladius sordidellus/psilopterus*-type (6%) and *Procladius* (6%). *Dicrotendipes nervosus*-type (20%) and *Ablabesmyia* (10%) appear for the first time in this zone and are the most dominant taxa. Warm water taxa make up around half of the chironomid community in zone 2. Taxa linked with cooler, less productive conditions fall such as *Micropsectra insignilobus*-type (3%), *Tanytarsus lugens*-type (<1%) and *Protanypus* (<1%), fall dramatically in this zone. *Heterotanytarsus* (3.5%), which has been linked with bog environments in the Irish training set (Potito *et al*., forthcoming), also appears for the first time in this zone, which could indicate the beginning of bog development in the catchment. Reconstructed chironomid-inferred temperatures peak at 9,607 cal. yr BP, reaching 15.1˚C. Head capsule concentrations increase to an average of 38 head capsules ml^{-1} and diversity increases to 0.9.

8.3.3 Zone 3 (8,250 – 7,700 cal. yr BP)

Zone 3 is characterised by the increased prevalence of taxa associated with cooler, less productive lake conditions, such as *Psectrocladius septentrionalis*-type (19%), *Heterotrissocladius marcidus*-type (6%), *Pseudochironomus* (5%) and *Micropsectra insignilobus*-type (4%). *Psectrocladius septentrionalis*-type reaches its highest abundance between 8,100 cal. yr BP and 7,800 cal. yr BP. C-IT become cooler throughout this zone, where values fall to 13˚C by 7,700 cal. yr BP. Warmer water taxa such as *Dicrotendipes nervosus*-type decrease through this zone, while other warm water taxa, such as *Chironomus anthracinus*-type and *Tanytarsus mendax*-type, disappear entirely in zone 3. *Lauterborniella* is only present in the lake between 8,200 cal. yr BP and 8,000 cal. yr BP, and is associated with more intermediate temperature conditions. Diversity remains similar to zone 2 at 0.9, while head capsule concentrations increases to 43.7 head capsules ml^{-1}.

8.3.4 Zone 4 (7,700 – 6,000 cal. yr BP)

Taxa indicative of cooler water conditions, such as *Heterotrissocladius marcidus*-type, *Thienemannimyia*, *Pseudochironomus* and *Micropsectra insignilobus*-type, are abundant at the beginning of the zone between 7,700 to 7,550 cal. yr BP, and decrease quickly after 7,550 cal. yr BP. The dominance of *Tanytarsus chinyensis*-type (18%), which is associated with cooler lake conditions, suggests that temperatures were likely lower in this zone when compared to zone 2. However, taxa associated with warmer, more productive lake conditions, such as *Dicrotendipes nervosus*-type (17%), *Microtendipes pedellus*-type (~8%), *Tanytarsus glabrescens*-type (6%), *Tanytarsus mendax*-type (3%) and *Corynoneura edwardsi*-type (2%), are still abundant in this zone. Reconstructed C-ITs provides evidence for cooling at the start of the zone. At 7,500 cal. yr BP temperatures fall to 12.7˚C. C-IT show gradual warming throughout the rest of the zone, reaching values of 14.5˚C by 6,000 cal. yr BP. Finally, head capsule concentration increases to 60 head capsules ml^{-1} and diversity increases to 1.0.

8.3.5 Zone 5 (6,000 – 1,500 cal. yr BP)

Overall, zone 5 is dominated by *Tanytarsus chinyensis*-type (19%), *Tanytarsus mendax*-type (10%) and *Tanytarsus glabrescens*-type (8%), together comprising around one third of the chironomid community in the zone. *Heterotanytarsus* (14%) is also quite prominent throughout the zone, likely indicating an increase in the development of peat bog in the lake catchment. A notable decrease in *Dicrotendipes nervosus*-type takes place in this zone. C-ITs reveal a 2˚C fall in temperature over the 350 year period between 6,000 cal. yr BP and 5,650 cal. yr BP. Taxa indicative of cooler, less productive lake conditions increase in numbers over this period, namely *Heterotrissocladius marcidus*-type (2-14%), *Tanytarsus chinyensis*-type (23-34%) and *Thienemannimyia* (4-11%). Meanwhile, taxa linked with warmer, more productive lake conditions decrease in abundance over this period. These include *Dicrotendipes nervosus*-type (15-0%), *Polypedilum nubifer*-type (7-0%), *Microtendipes pedellus*-type (7-3.5%), *Tanytarsus mendax*-type (2-0%) and *Tanytarsus glabrescens*-type (11-6.5%). Apart from the rapid change in temperature evident in zone 1, the deterioration in temperature between 6,000 to 5,650 cal. yr BP shows the fastest rates of change in the Lough Nakeeroge core. After 5,650 cal. yr BP temperatures warm gradually, with a minor cooler period between 4,000 and

3,600 cal. yr BP and a more abrupt cooling phase evident between 1,980 and 1,650 cal. yr BP. The former cooling phase shows a decline of ~1˚C over this 500 year period, with *Microtendipes pedellus*-type, *Procladius* and *Tanytarsus glabrescens*-type declining rapidly after 4,100 cal. yr BP. *Procladius* does not increase again until 3,200 cal. yr BP, while *Tanytarsus glabrescens*-type re-emerges at 3,400 cal. yr BP. *Microtendipes pedellus*-type does not return for the remainder of the stratigraphy. The cooling phase between 1,800 and 1,650 cal. yr BP shows a more rapid ~1˚C decline in temperature over 200 years, with a notable increase in taxa associated with cooler, less productive lake conditions, such as *Thienemannimyia*, *Micropsectra insignilobus*-type and *Heterotrissocladius marcidus*-type. C-ITs provide evidence for a subsequent warming phase for the rest of the core with summer temperatures of ~13.9˚C between 1,600 and 1,500 cal. yr BP.

8.3.6 Chironomid Community Change

PCA Axis 1 explains 36.7% of the variance in the chironomid data, while Axis 2 explains a further 11.1% of the variance (Figure 8.6). The PCA ordination applied to the chironomid stratigraphy provides a clear overview of general lake development over the Holocene along PCA Axis 1. This change is more subtle after 6,000 cal. yr BP (Figure 8.6), when organic carbon and the chironomid community display less variability, likely indicating that the lake environment has stabilised. Generally, samples to the top of the bi-plot appear to contain a higher level of taxa associated with colder conditions, while samples to the bottom of the bi-plot appear to comprise of warmer water taxa (Figure 8.7).

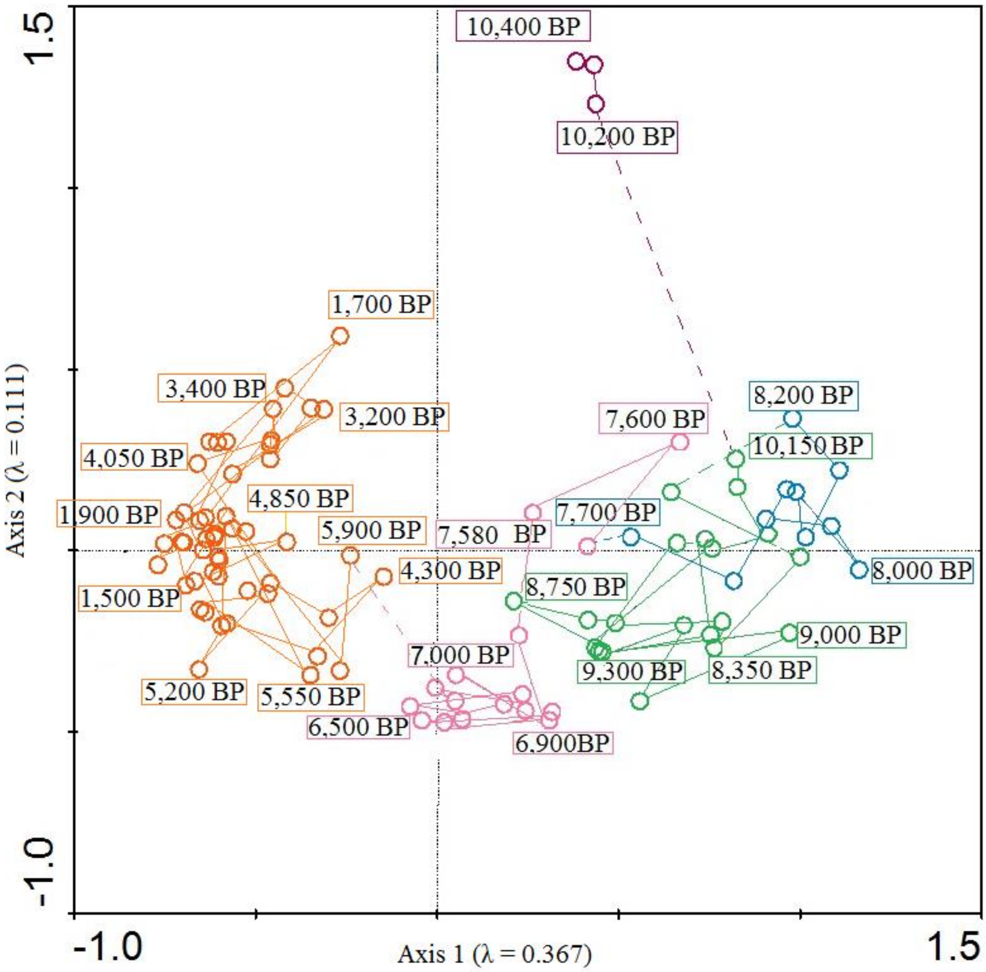
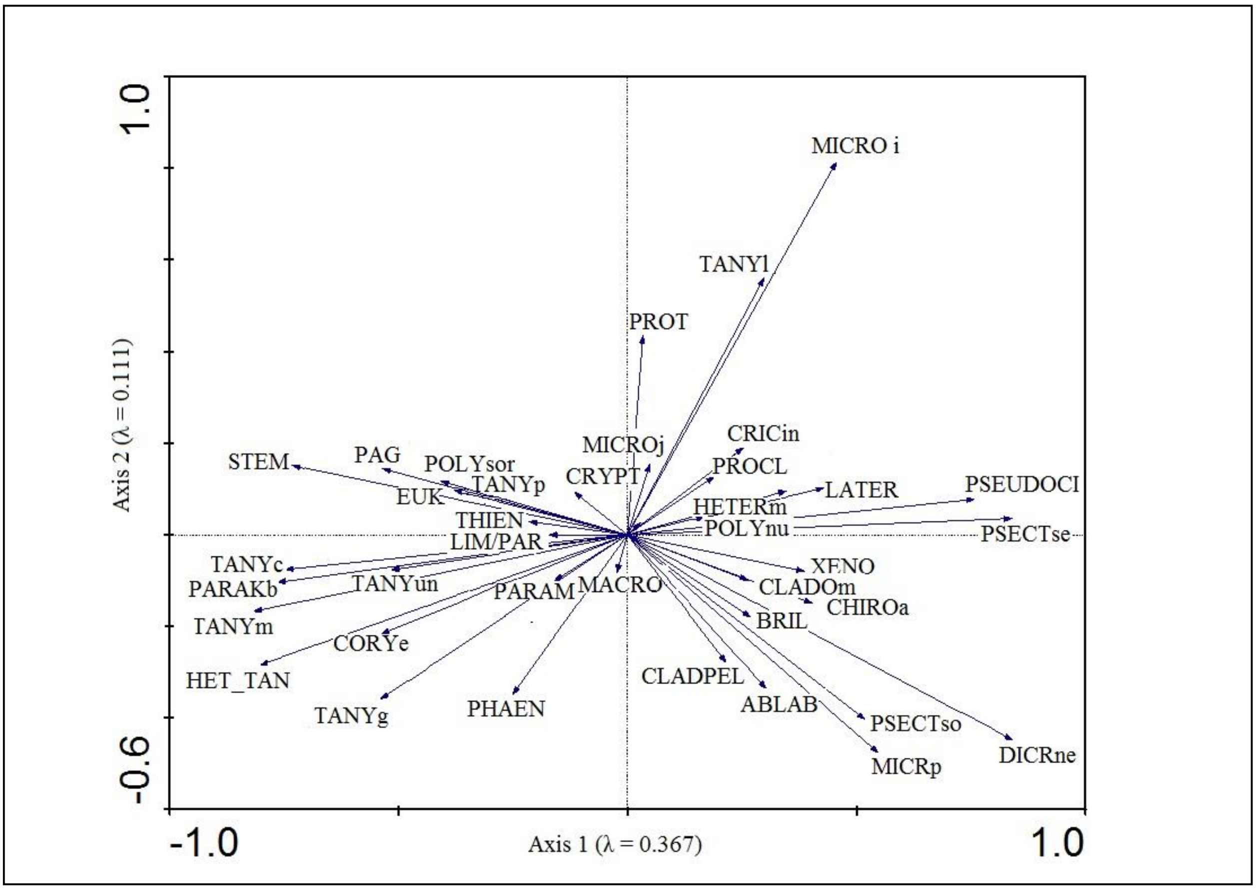


Figure 8.6 PCA bi-plots for samples. Zone 1 = Purple. Zone 2 = Green. Zone 3 = Blue. Zone 4 = Pink. Zone 5 = Orange.



Legend

Code name	Taxa full name	Code name	Taxa full name
ABLAB	*Ablabesmyia*	*PARAM*	*Paramerina*
BRIL	*Brillia*	*PHAEN*	*Phaenopsectra*
CHIROa	*Chironomus anthracinus*- type	*POLYnu*	*Polypedilum nubifer*- type
CLADOm	*Cladotanytarsus mancus*- type	*POLYsor*	*Polypedilum sordens*- type
CORYe	*Corynoneura edwardsi*- type	*PROCL*	*Procladius*
CRICin	*Cricotopus intersectus*- type	*PROT*	*Protanypus*
CRYPT	*Cryptochironomus*	*PSECTse*	*Psectrocladius septentrionalis*- type
DICRne	*Dicrotendipes nervosus*- type	*PSECTso*	*Psectrocladius sordidellus/psiloperus*- type
ENDOim	*Endochironomus impar*- type	*PSEUDOCI*	*Pseudochironomus*
EUK	*Eukiefferiella claripennis*- type	*STEM*	*Stempellinella*
HET_TAN	*Heterotanytarsus*	*STICTr*	*Stictochironomus rosenschoeldi*- type
HETERm	*Heterotrissocladius marcidus*- type	*TANYc*	*Tanytarsus chinyensis*- type
LATER	*Lauterborniella*	*TANYg*	*Tanytarsus glabrescens*- type
MACRO	*Macropelopia*	*TANTl*	*Tanytarsus lugens*- type
MICROj	*Micropsectra junci-type*	*TANYm*	*Tanytarsus mendax* -type
MICROi	*Micropsectra insignilobus-type*	*TANYp*	*Tanytarsus pallidicornis*- type
MICRp	*Microtendipes pedellus-type*	*TANYun*	*Tanytarsus* undiffrenciated
PAG	*Pagastiella*	*XENO*	*Xenochironomus*
PARAKb	*Parakieferiella bathophila*- type		

Figure 8.7 PCA bi-plot for common taxa.

The samples in zone 1 are clustered towards the top of the graph and an overview of the environmental preferences of the taxa indicates that zone is dominated by cool-adapted taxa, such as *Micropsectra insignilobus*-type, *Tanytarsus lugens*-type and

Protanypus (Figure 8.7). The transition from zone 1 to zone 2 can be seen as a shift from the top of the bi-plot along PCA Axis 2 ($\lambda = 0.111$). Samples in zone 2 are comprised of *Dicrotendipes nervosus*-type, *Microtendipes pedellus*-type and *Psectrocladius sordidellus/psilopterus*-type, which are associated with warm, productive lake conditions. The transition from zone 2 to zone 3 can be explained by a shift further to the right of the bi-plot and towards the top along PCA Axis 2. The samples in zone 3 are dominated by *Pseudochironomus* and *Psectrocladius septentrionalis*-type, indicating a shift to cooler conditions. The transition from zone 3 to zone 4 can be seen as a shift towards the left hand side of the bi-plot. At 7,000 cal. yr BP samples in zone 4 shift towards the bottom of the bi-plot, likely due to a fall in the number of cooler water taxa in these samples and an increase in warm water taxa, such as *Tanytarsus mendax*-type and *Tanytarsus glabrescens*-type. The final transition, from zone 4 to zone 5, is characterised by a further shift to the left of the bi-plot. These samples are largely dominated by *Tanytarsus chinyensis*-type and *Parakiefferiella bathophila*-type.

8.4 SYNOPSIS

Chironomid-inferred temperatures over the Holocene have largely fluctuated within the prediction error of the inference model, leading to potential errors in interpretation. However, the centennial-scale temperature changes inferred from the Lough Nakeeroge chironomid record are largely in agreement with climate trends and climate events inferred from other palaeoclimate records in Ireland and Europe. Zone 1 is dominated by taxa associated with cool, oligotrophic lake conditions. Lowest C-IT of 12.5˚C is observed at 10,200 cal. yr BP, in line with a trough in sediment organic carbon (Figure 8.8). This time period is also marked by a high concentration of chironomid head capsules and pollen grains, as well as low organic content, likely indicative of low sedimentation rates between during this time. These two samples are likely older than estimated within the age-depth model (discussed above), and represent early Holocene lake development and warming. C-IT estimates in Lough Nakeeroge show a notable warming trend until 9,600 cal. yr BP (Figure 8.8), which represented the Holocene Thermal Maximum (HTM) for this reconstruction.

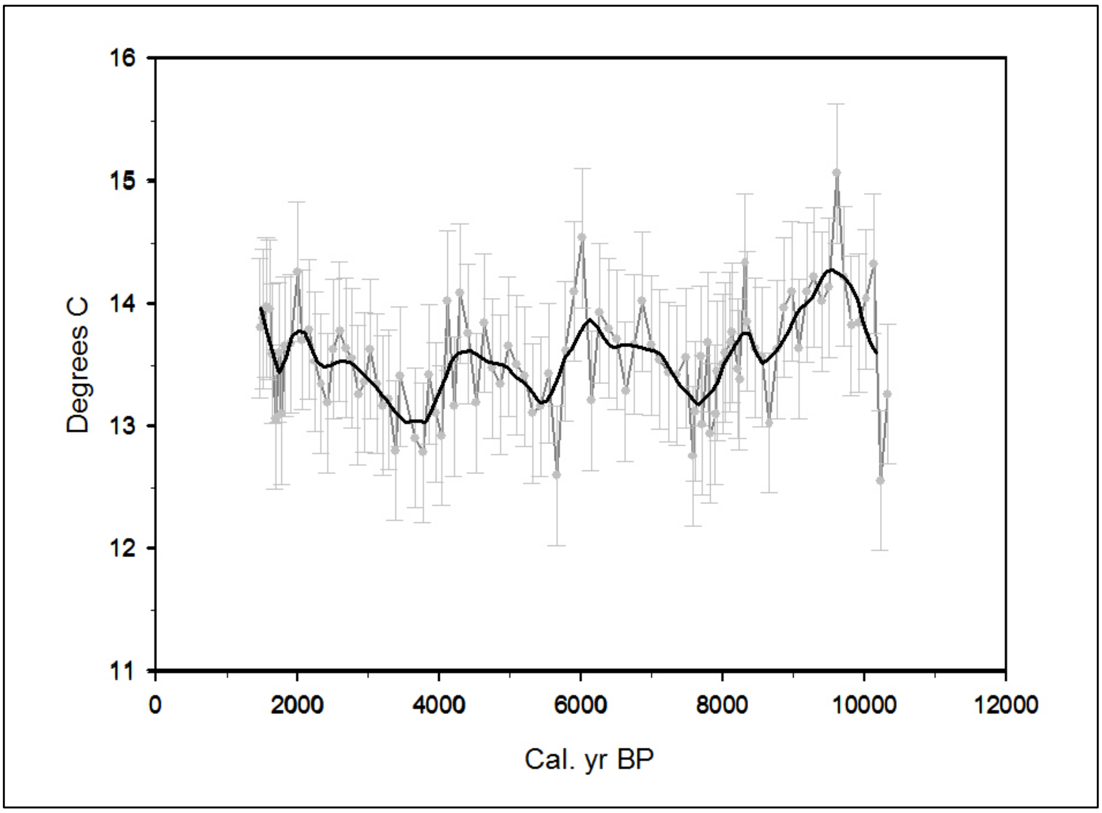


Figure 8.8 Chironomid-inferred temperature from Lough Nakeeroge with LOESS smoother (span = 0.1). Error bars show standard errors for the reconstructed temperatures.

The timing of peak Holocene warmth in Europe is spatially variable (Kaufman *et al.*, 2004). Studies undertaken in northern Sweden (Laroque and Hall, 2003), Kola Peninsula (Ilyashuk *et al.*, 2005) and the eastern Alps in Austria (Ilyashuk *et al.*, 2011) indicate that the HTM occurred between 10,000 and 9,000 cal. yr BP. However, other sites in northern and central Fennoscandia (Velle *et al.*, 2005; Seppä *et al.*, 2002; Rosén *et al.*, 2001), northern Iceland (Caseldine *et al.*, 2006) and Scotland (Edwards *et al.*, 2007) suggest that the HTM was not reached until around 8,000-7,000 cal. yr BP. Reconstructed summer temperatures from the Lough Nakeeroge core reach their highest levels of 15.1˚C at 9,600 cal. yr BP, although one sample at 6,000 cal. yr BP is also quite high with a value of 14.5˚C (Figure 8.8). The C-IT from the lake show sustained warmth between 9,700 and 8,800 cal. yr BP in western Ireland, following similar timing to northern Sweden, Austrian Alps and Kola Peninsula HTM.

Widespread cooling after early-Holocene warmth is a feature in most Holocene temperature studies in Europe. The C-ITs show a notable cooling trend from 9,150 cal. yr BP to 7,500 cal. yr BP. This period is of considerable interest as this cooling phase occurs around a well-documented abrupt cooling event termed the 8,200 yr event (Alley *et al*., 1997). Caseldine *et al*. (2006) found that temperatures in northern Iceland reduced well before this 8,200 yr event. Similar temperature declines over this time period have been identified in Switzerland (Heiri *et al*., 2004) and Scandinavia (Velle *et al*., 2005) through chironomid temperature reconstructions. C-ITs in this study suggest a slight warming phase between 8,400 cal. yr BP and 8,200 cal. yr BP, which coincides with a pollen perturbation in western Ireland (O'Connell and Molloy, 2005) and wetter conditions in southern Norway (Dahl and Nesje, 1996). Hereafter, temperatures deteriorate in the Lough Nakeeroge record and reach their lowest values between 7,800 cal. yr BP and 7,500 cal. yr BP, where temperatures fall by ~1˚C. Head *et al*. (2007) and Edwards *et al*. (2007) identify a 320 yr prolonged cool period in western Ireland and Scotland from 7,790 cal. yr BP to 7,470 cal. yr BP. A similar change in C-IT, along with a decline in woodland, has been identified in the Swiss Alps around 7,800 cal. yr BP (Heiri *et al*., 2003). No evidence of the 8,200 yr event was found in this core. Samples were taken at 4 cm (~105 yr) intervals throughout most of the core. Between 8,350 cal. yr BP and 7,600 cal. yr BP (321-292 cm), samples were taken every 26 to 79 years (Table 8.1). As the 8,200 yr event has been identified as lasting for ~60 years (Thomas *et al*. 2007), it is likely that this event was missed due to sampling resolution.

Table 8.1 Sampling interval between 7,582 cal. yr BP to 8,345 cal. yr BP.

Depth (cm)	Year (cal. BP)
292	7582
293	7608
296	7687
297	7714
300	7793
301	7819
304	7898
305	7924
308	8003
309	8029
312	8108
313	8134
316	8213
317	8239
320	8318
321	8345

C-IT show warming after 7,500 cal. yr BP, with temperatures reaching 14.5˚C by 6,000 cal. yr BP. Korhola *et al* (2002) showed that C-IT in northern Fennoscandia were warm and stable between 8,000 cal. yr BP and 5,800 cal. yr BP. Davis *et al.* (2003) suggest the temperatures in northwest Europe were highest ~6,000 cal. yr BP. Velle *et al.* (2005) argue that blocking anticyclones over northern Scandinavia replaced westerly winds by more southerly winds, bringing warmer conditions to western Europe during this time. In Ireland, Stolze *et al*. (2012) linked increased human settlement to a period of elevated summer temperatures and low rainfall between 5,800 to 5,550 cal. yr B.P. A wealth of palynological records from western Ireland broadly suggest climate amelioration between 6,000 cal. yr BP and 5,600 cal. yr BP in line with an increase in human activities (Stolze, 2013; Verrill and Tipping, 2010). This period is known as the Early Neolithic in Ireland and has been the focus of a number of archaeological and palaeoenvironmental studies, which have focused on the rapid increase in farming activity during this time (Stolze, 2013; 2012; Taylor *et al*., 2013; Cooney, 2007; O'Connell and Molloy, 2001).

Human impacts in western Ireland declined between 5,600 and 4,500 cal. yr BP, which has been associated with climate deterioration (Stolze *et al*., 2013; 2012;

Caseldine *et al*., 2005). Lough Nakeeroge C-IT shows an abrupt decline of 2˚C between 6,000 cal. yr BP and 5,650 cal. yr BP, with continued low temperatures until 5,300 cal. yr BP. In the Northern Hemisphere evidence for North Atlantic ice-rafting (Bond *et al*., 1997), alpine glacier advances (Denton and Karlén, 1973) and strengthened westerly wind regimes over the North Atlantic (Meeker and Mayewski, 2002) have been identified between 6,000 cal. yr BP and 5,000 cal. yr BP. Korhola *et al*. (2002a) identified pronounced climate cooling around 5,800 cal. yr BP in northern Fennoscandia, using chironomid-inferred temperatures. This temperature decline is further supported by maritime glacier fluctuations in western Norway, which suggest cold/dry conditions ~6,000 cal. yr BP (Nesje *et al*., 2000).

The timing of the cooling event in the Lough Nakeeroge C-ITs, between 6,000 cal. yr BP and 5,650 cal. yr BP, appears be a couple of hundred years older than that identified in the literature, which could be due to ^{14}C-dated bulk sediment yielding an older age-depth model. It is assumed that these mid-Holocene warming and cooling phases identified in the literature and in this study are indicative of the same event and the uncertainty in the timing of these phases lies in ambiguity of ^{14}C dating. Pollen analysis which is currently being carried out on the Lough Nakeeroge core will hopefully identify any dating problems through identification of well-documented events, such as the elm decline. Regardless of the timing of these events, the rate of temperature decline (2˚C in 350 years) provides the first quantitative estimates of mid-Holocene temperature change in Ireland.

Records in Europe show that the last 5,000 years have been characterised by a general cooling trend. C-IT from Lough Nakeeroge show a general cooling in the late Holocene, although temperatures warm from 3,600 to 1,500 cal. yr BP. The record is punctuated by notable broad cooling phase between 4,000 and 3,600 cal. yr BP, and a more abrupt cooling between 1,800 and 1,650 cal. yr BP. Following mid-Holocene warmth, numerous studies show late Holocene cooling as Neoglacial conditions establish (Korhola *et al*., 2002b; Seppä and Birks, 2002 and Rosén *et al*., 2001). A 0.5°C decline in temperature between 4,000 and 3,600 cal. yr BP is evident in the Lough Nakeeroge C-IT reconstruction. Evidence for decreased temperatures between ~4,200 cal. yr BP and ~3,600 cal. yr BP is found in numerous European records, from Austrian Alps (Ilyashuk *et al*., 2011), Southern Sweden (Jessen *et al*., 2005) and Western Norway (Nesje *et al*., 2001). Literature on the Neoglacial in

Europe has claimed that a strong relationship exists between low solar irradiance and reduced temperatures (Koch and Clague, 2006; Hormes *et al.*, 2006; Holzhauser *et al*., 2005; Maasch *et al*., 2005; Karlén and Kuylenstierna, 1996). This cooling instigated growth in mountain glaciers (Matthews and Quentin, 2008; Seierstad *et al*., 2002; Nesje *et al*., 2001) and the retreat of tree-lines (Barnett *et al*., 2001; Dahl and Nesje, 1996).

Finally, brief cold oscillation is evident in the Lough Nakeeroge C-ITs between 1,800 cal. yr BP and 1,650 cal. yr BP. Korhola *et al*. (2002a) points out that within a rather featureless late Holocene record in northern Fennoscandia, reconstructed chironomid temperatures have identified a cold event at 1,800 cal. yr BP. In an Irish context, pollen records have shown large-scale woodland regeneration between ~1,750 cal. yr BP and ~1,450 cal. yr BP. This period, known as the Iron Age Lull, has been linked to a decline in farming activities (Newman et al., 2007; Molloy and O'Connell, 2004; O'Connell, 1994). It is not known if this phenomenon was culturally or climatically driven. The C-IT results from this study have identified a two pronged abrupt fall in summer temperatures of ~0.7°C at 1,800 cal. yr BP and again at 1,650 cal. yr BP. The C-IT reconstruction supports Irish tree-ring evidence that shows a change in environmental conditions between 1,743 cal. yr BP and 1,410 cal. yr BP (Baillie and Munroe, 1988). Water table reconstructions in Irish bogs (Swindle *et al*., 2010) suggest that the Irish climate was drier at this time. The results from this study propose that cooler temperatures may have occurred in Ireland at a time when climates were drier, likely instigating a shift in human activities during the Iron Age Lull.

CHAPTER 9: DISCUSSION

A debate surrounding the sensitivity of chironomids as reliable quantitative indicators of summer temperatures was reopened recently by Velle *et al*. (2012, 2010b). This paper states that chironomids can be used to reliably reconstruct temperatures over the late Glacial to early Holocene transition. However, they argue that other environmental pressures acting on lakes over the Holocene and recent past are likely confounding the ability of chironomids to quantitatively infer summer temperatures. While chironomid communities can be influenced by other environmental variables (Brooks, 2006; Heiri and Lotter, 2005, 2003), Brooks *et al*. (2012) argue that chironomids can provide powerful estimates of past Holocene temperatures. Numerous other studies provide evidence for summer temperature reconstructions over the Holocene, which are largely in agreement (Schmidt *et al*., 2011; Langdon *et al*., 2010b; Caseldine *et al*., 2006; Ilyashuk *et al*., 2005; Mayewski *et al*., 2004; Larocque and Hall, 2004; Heiri *et al*., 2003; Seppä *et al*., 2002; Rosén *et al*., 2001; Korhola *et al*., 2000b). Furthermore, chironomids have been shown to register small-scale temperature changes evident in meteorological records over recent centuries (Guo *et al*., 2013; Langdon *et al*., 2011; Porinchu *et al*., 2010, 2007; Laroque *et al*., 2009; Laroque and Hall, 2003). However, the majority of these studies have been carried out on high elevation and/or high latitude sites that are experiencing rapid climate warming. Little work has been undertaken in lower latitude and lower altitude locations as it is perceived that temperature change is not large enough to sufficiently influence the chironomid records. This study set out to test the sensitivity of chironomids from mid-latitude, low- to mid- elevation sites in western Ireland to temperature change at various timescales.

As each results chapter examined the study sites independently, it is important to combine the records in a more comprehensive synthesis to examine chironomid community response to both climate change and human impacts in western Ireland. In order to accurately compare chironomid community change to a climate record, long-term temperature trends needed to be established for the study region. This was done by reconstructing daily temperature from Markree Observatory from 1842 to 2011, and comparing this to existing long-term records to assess the unique temperature regime of the study area (McKeown *et al*., 2013). Chironomid community change was then compared to this newly-established temperature record to determine if chironomid communities from three different lakes are influenced by temperature through time. The identification of chironomid community response to recent instrumentally recorded climate change was made possible by adjusting all environmental and climate records to match the resolution of the lake data. Markree summer air temperature and seasonal precipitation data were averaged over each sediment interval in order to better represent climate conditions during that interval. This which allowed for a direct comparison between chironomid data and temperature change.

Chironomid communities' ability to respond to temperature can be confounded by human activities. In order to determine if the chironomid-temperature signal was decoupled by human land disturbance, chironomid histories were compared with known land-use histories for each of the three study lakes. As the effects of human activities at Lough Meenagraun and Lough Ballygawley were evident in the lake records, temperature was also found to have affected the chironomid communities. Lough Lumman was found to be more responsive to changes in lake level, with summer temperature only having a minor influence on the chironomid community.

The ability of chironomid communities to respond to subdued temperature changes from the late 19th century to the present, despite moderate human influences in the lake catchments, supports the further exploitation of lake sediment archives into the more distant past. The chironomid record from a fourth lake, Lough Nakeeroge, was used to infer broad-scale temperature fluctuations over the Holocene and further test the ability of chironomids to register a temperature signal over this period. Velle *et al*. (2010b) argue that several environmental variables can affect chironomids and interfere with chironomid-inferred temperature models over the Holocene. Shifts in trophic state were identified as the major environmental variable that could potentially decouple the chironomid-temperature relationship in lakes over the Holocene; pH and lake level changes are also important pressures (Velle *et al*., 2012, 2010b; Anderson *et al.*, 2008). Brooks *et al*. (2012) argue that summer temperature remains the dominant influence on chironomid communities despite natural changes in the development of lakes over the Holocene. However, large-scale human activities can strongly alter lake trophic status and tend to have a greater influence on chironomid communities.

Due to the geographic location of Lough Nakeeroge, only small-scale agriculture would have been practised on the catchment in the past. The results from Lough Meenagraun and Lough Ballygawley suggest that chironomid communities in western Ireland remain responsive to small-scale temperature change even with low to moderate human impacts with the catchments. The results from this lake show that the chironomid community was responsive to temperature change over the Holocene, as chironomid-inferred temperature changes are largely in agreement with other palaeoclimate records in the region.

9.1 RESEARCH HYPOTHESES

Four major research hypotheses were developed to address the thesis objectives. The findings from each hypothesis test are discussed below.

9.1.1 Long-term temperature trends at Markree Observatory are unique from existing (coastal) temperature records from the west of Ireland in that the record will exhibit characteristics of a more inland site due to geographic location and surrounding topography.

Results from the Markree reconstruction, and comparisons with other long-term records, show the unique temperature regime for the County Sligo region. The large diurnal ranges and low minimum temperatures show the potential influence of the surrounding topography on seasonal temperatures, as well as the importance of prevailing wind direction when considering coastal influences. As this record has been largely absent from past analyses of Ireland’s long-term temperature trends, it helps to increase the spatial coverage of the extended Irish climate chronology, especially for the western portion of the island.

The Markree record displays many characteristics of an inland locality, despite its close proximity to the coast. Markree’s low minimum temperatures and large diurnal range are similar to inland and eastern records such as those from Birr, Phoenix Park and Armagh. Furthermore, seasonal correlations between Markree and the other stations tend to be highest with Birr and Armagh, and lowest with Malin Head and

Valentia. This suggests that the Sligo region in the northwest of Ireland is somewhat sheltered from direct oceanic influences. Markree's geographic location, adjacent to the shallow Ballysadare Estuary and close to the mountains surrounding the northern and western areas of Sligo Bay, is sheltered from the moderating westerly/southwesterly wind regimes that largely govern the Irish climate. This places Markree Observatory further 'inland', sheltered from direct oceanic influences. Evidence for this is seen in all seasonal minimum long-term temperature records, where Markree consistently exhibits among the lowest values. In comparison, Valentia and Malin Head display the highest seasonal minimum temperatures. Subdued sub-decadal maximum warming and cooling throughout the Valentia and Malin Head records in all seasons is characteristic of more coastal locations, while maximum temperatures are notably warmer for more 'inland' stations, including Markree. The Markree record consistently exhibits greater maximum and minimum temperature variability when compared to the other five records over the past 135 years. The early portion of the Markree record could be noise within the dataset as a result of instrumentation and exposure defects. However, as the same variability is evident in the record post-1950, when recording measures were standardised across the country, it is highly likely that the large range in sub-decadal temperatures evident in the Markree record is due to the observatory's sheltered location, which buffers this site from the full effects of the Atlantic Ocean.

Markree also displays the greatest minimum warming since the mid-1980s in all seasons, particularly spring and autumn. This highlights the importance of the region in future climate change scenarios, particularly as it has been shown that recent minimum temperatures in Ireland are increasing at around twice the rate of maximum temperatures (McElwain and Sweeney, 2007, 2005; Zhai and Ren, 1999; Vincent and Gullet, 1999). Winter temperatures in 2010 and 2011 were characterised by notably cooler conditions. This cold spell highlights that, despite a recent warming trend, extreme events can still occur. Similar cold spells are displayed over the Markree reconstruction, the coldest taking place in 1879 when the average winter daily minimum value was -2.28˚C. This exceptionally cold year has been linked to volcanic activity in Iceland and a solar minimum in December 1878 (Hickey, 2012). 2010 was the sixth coldest year on record, with a winter mean minimum value of -1.20˚C, while 2011 was the thirteenth coldest year with a winter mean minimum of

-0.42˚C. This places the recent cold anomaly in a broader context and emphasises the need for this longer term record to be included in future climate research, especially in a region that experiences such low minimum temperatures. Although the NAO predictably showed a strong relationship with winter temperatures from all stations (McElwain and Sweeney, 2003), the only discernible geographic trend was that Malin Head (on the north coast) consistently displayed the weakest relationship with winter NAO. Finally, the three coastal stations located in the north, southwest and northwest of the island (Malin Head, Valentia and Markree, respectively) all display different seasonal temperature trends, highlighting the unique regional climate regimes that exist in north and western Ireland. It was important to establish a unique climate time-series for the study region, as it allowed for greater accuracy in comparing recent temperature change with palaeolimnological changes through time.

9.1.2 Chironomid communities in western Ireland lakes are responsive to recent summer temperature change, including recent climate warming.

It is now widely recognised that recent climate warming, resulting from anthropogenic activity, is having a notable impact on aquatic environments (IPCC, 2007). Chironomid assemblages in high latitude or high altitude locations have been shown to be responsive to recent climate warming over the 20th century (Guo *et al*., 2013; Porinchu *et al*., 2010, 2007; Axford *et al*., 2009). While these studies have provided valuable information on the sensitivity of chironomids to recent temperature change, little work has been carried out on lower latitude, lower altitude locations, as it is often assumed that other influencing factors will confound a temperature signal. This study sought to investigate such a scenario and provide further evidence of the sensitivity of chironomids to more subtle, but still evident, temperature change experienced in less extreme locations.

The chironomid communities from two lakes, Lough Meenagraun and Lough Ballygawley, proved to be climatically sensitive, with chironomid-inferred temperatures (C-IT) following Markree temperature trends, particularly over the most recent decades. In Figure 9.1, the C-IT for all three lakes are presented. They are at different resolutions due to differing sediment accumulation rates, meaning that each 0.5 cm encompasses a varying number of years. However, general trends are evident, with the warmest years from 1990 to 2006, while cooler C-IT in the late 19th and early 20th centuries are evident in both Lough Meenagraun and Lough

Ballygawley. Lough Meenagraun C-IT ranged from 12.4°C to 13.2°C between 1868 and 2009, with a notable warming rate of 2°C/100 yrs from the mid-1990s to 2006. A subsequent cooling trend between 2008 and 2009 has essentially altered this rate of warming from 1995 to 2009 to 0.5°C/100 yrs. For Lough Ballygawley, C-IT ranged from 14.3°C to 15.3°C between 1878 and 2009. The time period between the early 1980s and 2006 displays a rate of warming of 1.7°C/100 yrs. As with the Lough Meenagraun C-IT, 2008 and 2009 mark years with cooler summer temperatures, modifying the rate of warming from the early 1980s to 2009 to 1.1°C/100 yrs. The C-IT model at Lough Meenagraun appears to be following the Markree mean July temperature record more closely than the mean summer temperature record over the entire 20th century. Furthermore, the C-IT reconstruction peaks with the warmest July years, as calculated for each sediment interval. The Lough Ballygawley C-IT follows a similar trend to the Markree mean summer temperatures. This emphasises the complexity of the chironomid response to summer air temperature, indicating that years with heat waves in July may have a notable impact on some chironomid communities, while mean summer temperature trends will have an over-riding influence on others. The difference between the two chironomid community responses to temperature change could be due to site-specific differences in lake productivity, lake morphology and water chemistry. Differences in inferred temperatures could also be due to the fact that temperature changes are within the prediction errors of the inference model (0.51˚C). Despite the minor differences in C-IT models from Lough Meenagraun and Lough Ballygawley, an increase in warm water taxa is a key feature in the 1990s in both lakes.

Furthermore, redundancy analysis shows that samples from Lough Meenagraun follow temperature trends from the mid-1980s to present. It also shows that summer temperature is the most important control on the chironomid community throughout the Lough Ballygawley record. The results show that chironomid assemblages from these two lakes are responsive to recent temperature change, providing evidence that chironomids can reflect modern temperature changes in mid-latitude, low- to mid-altitude locations. Finally, the chironomid community at Lough Lumman was found to be more responsive to precipitation patterns and associated lake level change than to temperature change. The presence of prominent shallow shelves in the lake basin could potentially confound the ability of chironomids to register a temperature signal. This emphasises the importance of lake morphology when determining the potential for a lake to register a specific temperature signal.

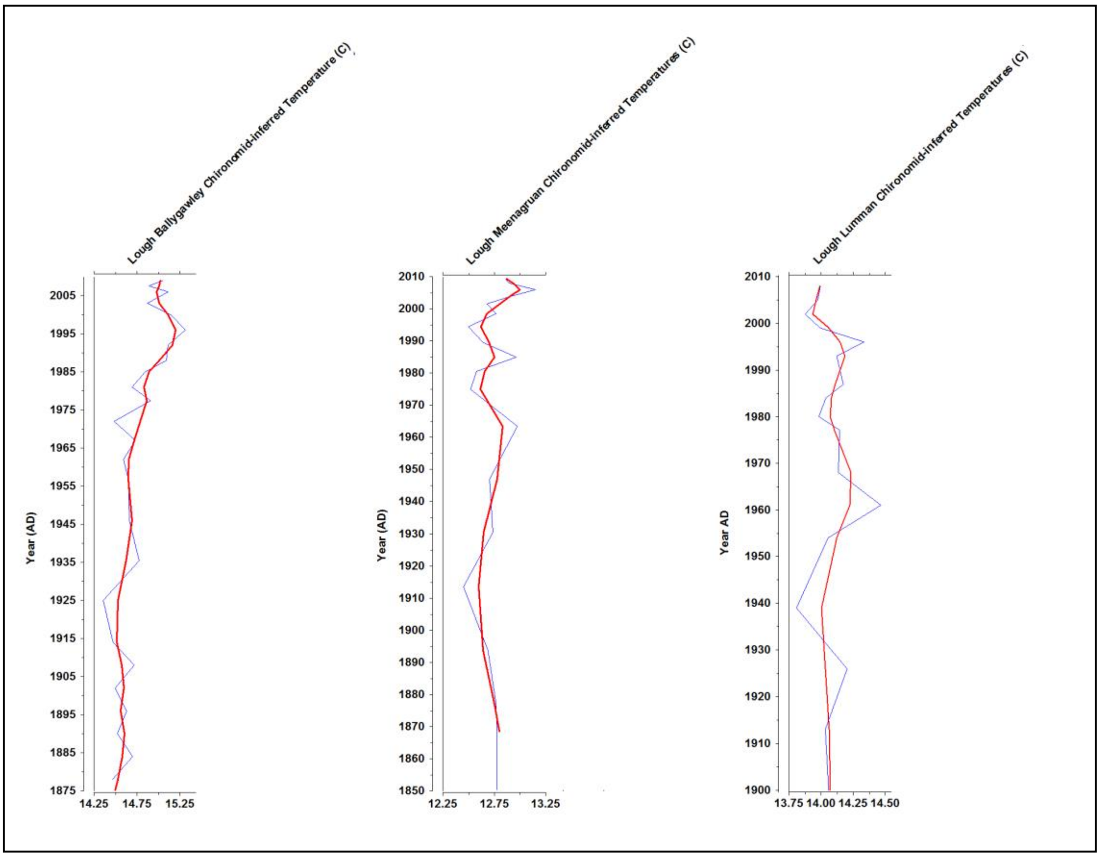


Figure 9.1 Chironomid-inferred temperature reconstructions for Lough Meenagraun, Lough Ballygawley and Lough Lumman with ^{210}Pb dates.

9.1.3 The temperature signal and land-use changes can be identified and teased apart in the chironomid record.

Nutrient conditions and trophic state co-vary with temperature, making it difficult to distinguish chironomid community response to changes in one or both of these variables. Confusion can occur as chironomid taxa characteristic of warm water lakes are also characteristic of productive, eutrophic waters, while cold water taxa are also associated with oligotrophic lake conditions (Brooks *et al*., 2010). Teasing apart the climate signal from other environmental influences is often done through redundancy analysis (Bennion *et al*., 2012) or through direct time-series comparisons with climate and land-use records (Guo *et al*., 2013). Both of these methods were employed in this study. In Ireland, agriculture is the main human activity that is largely responsible for nutrient loading in lakes (Ulén *et al*., 2007). It has been found that human activities that strongly affect the nutrient loading of lakes can lead to abrupt shifts in chironomid communities (Taylor *et al*., 2013; Gathorne-Hardy *et al*., 2009, 2007; Heiri and Lotter, 2005, 2003). This study investigated if chironomid response to changes in land-use can be divorced from a temperature signal.

There is an evident shift in the Lough Meenagraun chironomid community in the mid-19th century. Evidence extracted from historical land-use records indicates that sheep farming increased in the area after 1850. The change in taxa assemblage at this time corresponds with a shift in agricultural activity that took place in the surrounding Glenade area. Taxa associated with eutrophic lake conditions in areas with agricultural activity, as identified in the Irish training set (Potito *et al*., forthcoming), including *Tanytarsus pallidicornis*-type, *Microtendipes pedellus*-type, *Procladius* and *Polypedilum nubifer*-type, abruptly increase in abundance around 1850. This change in catchment land-use may also account for other shifts in midge community structure. The presence of taxa associated with terrestrial environments, such as *Bryophaenocladius* and *Smittia*, indicate a potential erosion event around 1850. This is further supported by a fall in *Cladotanytarsus mancus*-type, which is associated with the presence of coarse sediments on submerged banks (Luoto *et al*., 2008), possibly indicating an erosion event. Furthermore, increasing numbers of *Limnophyes/Paralimnophyes* and *Pseudosmittia* (both indicative of terrestrial/semi-terrestrial environments) post-1850 suggest that the level of the lake may have increased, flooding surrounding shelves. Evidence of ‘new’ large boulders around one of the outlet channels also suggests that the lake was likely dammed in conjunction with the intensification of land-use.

Heterotanytarsus, which thrives in humic waters, became more dominant post-1850, indicating that the input of peat material surrounding the lake likely increased, creating greater humic water conditions in which this taxon has been known to thrive (Cranston, 1982; Saether, 1979; Brudin, 1949). The greater input of peat material could have resulted from increased animal grazing. The level of organic carbon also increased at this time, which could also be due to increased input of peat. Furthermore, the lake was likely dammed at this time, causing the lake level to increase and flood the surrounding shelves. *Limnophyes/Paralimnophyes* (semi-terrestrial/terrestrial taxon) is associated with high organic carbon along RDA Axis

1, along with *Heterotanytarsus*. This signifies that LOI could be related to changes in lake level and the increased input of peat material as a result of human activity at this site since 1850. The increase in taxa associated with eutrophic and productive lake conditions after 1850 further supports the assumption of increased pastoral activity within the lake catchment. Despite a significant human influence within the Lough Meenagraun catchment from around 1850, chironomid communities still register a temperature signal over the instrumental period. Although LOI proved to be the most dominant environmental variable through the dated portion of the record, redundancy analysis showed that samples followed an increasing temperature trend from 1985 to 2009.

Changes in the chironomid community from Lough Ballygawley have also been shown to respond to land disturbances, evidenced from historical records. A notable shift from eutrophic lake conditions to more oligotrophic conditions takes place around 1850. A decline in intensive arable farming around 1850 is likely to have taken place at this time, as a result of the large-scale shift in agriculture intensity caused by the Great Irish Famine of 1845-1849. This could have promoted a growth in the dominance of oligotrophic species and a decline in taxa associated with eutrophic lake conditions. In the late 19th century, lake conditions became more eutrophic once again, with an increase in taxa associated with mesotrophic-to-eutrophic conditions and a fall in taxa linked with oligotrophic lake conditions. This is likely to be a result of increased farming activities in the late 19th century once socio-economic conditions improved after the Famine. Taxa associated with eutrophic lake conditions increase throughout the 20th century, while taxa associated with oligotrophic lake conditions, particularly *Stempellina,* decrease over this time. A notable peak in the numbers of *Stempellinella* in the 1950s corresponds with a peak in taxa associated with eutrophic lake conditions. This occurs at a time when a scheme was introduced at a national level to promote the use of fertilisers in arable farming.

Lough Ballygawley experienced a significant disturbance when the lake was drained in the late 19th century and again in 1920 (Goodwillie *et al*., 1992). Evidence for this was found in historical documentary sources and is supported by an increase in the numbers of *Limnophyes/Paralimnophyes* (associated with terrestrial/semi-terrestrial environments) on both occasions. It was common practice to drain lakes at this time for land reclamation (Goodwillie *et al*., 1992). Despite these changes in lake trophic state and lake level at Lough Ballygawley, the C-IT have been shown to follow similar patterns to the Markree mean summer temperature record. Summer temperature displays the strongest relationship with RDA Axis 1 while partial RDAs indicate that summer temperature is the only significant environmental variable, explaining 10.6% of the variance.

Low impact human pressures on the lake catchments of Lough Ballygawley and Lough Meenagraun are evident and can be identified by the changes in the chironomid community. In spite of this, C-IT models can still yield a temperature signal. The chironomid community in Lough Ballygawley was shown to be particularly responsive to the temperature change evident in the instrumental record. Warming summers may be enhancing algae productivity in this shallow, productive lake over the 20th and early 21st centuries. Eggermont and Heiri (2011) argue that the chironomid-temperature relationship may be driven by direct and indirect effects of temperature on in-lake and/or catchment variables, in-turn having a strong influence on chironomid community composition. Recent studies show that the direct effects of rising temperatures increase nutrient loading in lakes through enhanced rates of mineralisation in catchment soils (Brookshire *et al*., 2011; Moss *et al*., 2011; Jeppesen *et al*., 2010; Rustad *et al*., 2001). As the chironomid-temperature relationship is strong in Lough Ballygawley, the chironomid community may be responding to temperature change directly, and also indirectly, as a result of enhanced algae productivity. Such a scenario was found in southwest China where chironomids were used to tease apart a temperature signal from human impacts in a high elevation lake (Guo *et al*., 2013). Similarly, lake productivity and summer air temperature were deemed important controls on the chironomid community at this site over the 20th century. Therefore, the effect of climate warming and lake productivity on chironomid communities in shallow lakes merits further investigation.

The chironomid community from Lough Lumman is being driven by different catchment pressures, and there is no documentary or field-based evidence of human influence on the lake or its catchment. It is assumed that, at least over the ^{210}Pb-dated section of the core, the chironomid community at the lake is being driven by natural environmental or within-lake variables. The morphology of Lough Lumman is notably different from the other sites, with prominent shallow shelves along the northern and western areas of the lake basin. C-IT compared with meteorological recordings since 1900 indicate that the chironomid assemblages at the lake are not responding to temperature change. Instead, it is likely that changes in chironomid populations are driven by seasonal precipitation change and associated fluctuations in lake levels. Evidence from RDA analysis shows that LOI, along with winter and spring precipitation, is the most important variable influencing the chironomid community. It is likely that fluctuations in organic carbon levels in the lake are related to changes in lake level, which is driven by winter and spring precipitation. Here the prominent shelves are likely flooded during years in which winter/spring precipitation was high. In turn, when winter/spring precipitation was low, taxa associated with terrestrial/semi-terrestrial environments increased due to lower lake levels along the lake shelves. Such changes in winter precipitation are driven by changes in the NAO. Consequently, the chironomid-inferred temperature reconstruction does not accurately represent a temperature change through time. Adrian *et al*. (2009) proposed that the strength of a proxy indicator to infer a specific climate variable can be dependent on the physical characteristics of the lake. This emphasises the importance of selecting study lakes with a simple morphology, as hydromorphological pressures can confound the ability of chironomids to register a temperature signal.

9.1.4 Chironomid communities in western Ireland are responsive to regional temperature fluctuations through the Holocene.

Although the climate of the Holocene promoted the growth of human societies, less is known about the climate variability over this period in Ireland. The vast majority of Irish Holocene studies have tended to focus on human impacts on the landscape using pollen (Caseldine *et al*., 2007; Edwards *et al*., 2007; Mitchell *et al*., 2006; Caseldine *et al*., 2005; Ghilardi and O'Connell, 2005; Molloy and O'Connell, 2004, 2002, 1995, 1992, 1991; Huang, 2002; O'Connell and Molloy, 2001; Jeličič and O'Connell, 2001; Edwards, 1985; Lynch, 1981), with little work undertaken on identifying the climate fluctuations over this period. Studies that have investigated Holocene climate change in Ireland have shown a number of climate events, including at 5,200–5,100 cal. yr BP, believed to be linked to increased storm activity

(Caseldine *et al*., 2005); the 4,200 cal. yr BP event, which has been linked to wetter conditions (Swindle *et al*., 2012); and the 8,200 cal. yr BP cold event (Ghilardi and O'Connell, 2013; Head *et al.,* 2007), which has been well-documented across Europe. The Holocene temperature record produced as part of this thesis is the first quantitative temperature reconstruction over the Holocene in western Ireland.

This study was also the first chironomid-inferred temperature reconstruction to be created using Potito *et al.*'s (forthcoming) Irish training set. The temperature trends inferred from the Lough Nakeeroge chironomid record are largely in agreement with the climate history inferred from other proxies in Europe. The chironomid community in Lough Nakeeroge proved to be temperature-sensitive over the Holocene, with temperatures ranging from 12.5˚C to 15.1˚C between 10,330 cal. yr BP and 1,500 cal. yr BP. To sum-up the findings, the early-Holocene marks the period with the greatest temperature changes. The coolest period was evident at the beginning of the record, while the Holocene Thermal Maximum occurred at 9,600 cal. yr BP. The results from this study are largely in agreement with HTM timing from northern Sweden (Laroque and Hall, 2003), Kola Peninsula (Ilyashuk *et al*., 2005) and the eastern Alps in Austria (Ilyashuk *et al.,* 2011), where temperatures are estimated to have peaked between 9,700 cal. yr BP and 8,800 cal. yr BP. The magnitude of maximum warmth inferred from other chironomid-inferred temperature reconstructions appears have been largely similar throughout northwestern Europe (Ilyashuk *et al*., 2011; Edwards *et al*., 2007; Caseldine *et al*., 2006; Ilyashuk *et al*., 2005; Velle *et al*., 2005; Laroque and Hall, 2003; Seppä *et al*., 2002; Rosén *et al*., 2001).

Widespread cooling after early-Holocene warmth is a feature in most Holocene temperature studies in Europe. This period is of considerable interest as this cooling phase occurs around a well-documented abrupt cooling event termed the 8,200 yr event (Alley *et al*., 1997). This cooler period is evident over much of the Northern Hemisphere (Caseldine *et al*., 2006; Velle *et al*., 2005; Heiri *et al*., 2004) due to large-scale strengthening of atmospheric circulation over the North Atlantic and an increase in the frequency of winter westerly wind regimes (Mayewski *et al.,* 2004). However, the timing of this prolonged cool period has been identified as occurring much later in lower latitude locations (Head *et al*., 2007; Edwards *et al*., 2007; Heiri *et al*., 2003). This is evidenced in the Lough Nakeeroge C-IT, where temperatures notably decline between 9,150 cal. yr BP and 7,500 cal. yr BP. This study provides further evidence of a prolonged cool period in lower latitude locations.

Before this study, little was known about temperature fluctuations throughout the full Holocene in Ireland, which is surprising as anecdotal evidence between societal change and climate change has been inferred in palynological studies from the west of the island (Stolze, 2013; Verrill and Tipping, 2010). These studies broadly suggest climate amelioration between 6,000 cal. yr BP and 5,600 cal. yr BP in line with an increase in human activities. Furthermore, a decline in human impacts on the landscape between 5,600 cal. yr BP and 4,500 cal. yr BP has been linked with climate deterioration in western Ireland (Stolze *et al*., 2013, 2012). While these studies provide important insights into societal change at these times, before now, no quantitative estimates of temperature change were available to support these assumptions. Temperatures inferred from the Lough Nakeeroge chironomid community provides evidence for warming after 7,500 cal. yr BP, with temperatures reaching 14.5˚C by 6,000 cal. yr BP. A subsequent abrupt decline of 2˚C in CI-T was identified between 6,000 cal. yr BP and 5,650 cal. yr BP, with continued lower temperatures until 5,300 cal. yr BP. The rate of temperature decline (2˚C in 350 years) provides the first quantitative temperature estimates for this time period. This study provides evidence that supports the findings by Stolze *et al*. (2013, 2012), where climate variability could be linked to Neolithic human activity in western Ireland.

Temperature reconstructions in Europe show that the last 5,000 years has been characterised by a general cooling trend. C-IT from Lough Nakeeroge largely follow this pattern, where cooler temperatures are a feature of the late Holocene, albeit with a warming trend between 3,600 cal. yr BP and 1,500 cal. yr BP. Furthermore, there is a notable cooling phase between 4,000 cal. yr BP and 3,600 cal. yr BP in the Lough Nakeeroge record. A cooling of 0.5°C between 4,000 cal. yr BP and 3,600 cal. yr BP is evident in the record and is supported by numerous European records, such as the Austrian Alps (Ilyashuk *et al*., 2011), southern Sweden (Jessen *et al*., 2005) and western Norway (Nesje *et al*., 2001). This cooler period is not captured in all European palaeo-temperature reconstructions.

A final brief cold period is evident in the chironomid community from Lough Nakeeroge between 1,800 cal. yr BP and 1,650 cal. yr BP. A similar decline in C-IT is evident in northern Fennoscandia at 1,800 cal. yr BP (Korhola *et al.*, 2002b). Irish pollen records have shown broad-scale woodland regeneration between ~1,750 cal. yr BP and ~1,450 cal. yr BP as a result of reduced farming activities (Newman *et al.*, 2007; Molloy and O'Connell, 2004; O'Connell, 1994). This period is recognised as the Iron Age Lull in Irish literature. However, it is not known if this phenomenon is culturally or climatically driven. In Ireland, temperature change at this time has been largely unexplored. However, previous studies have identified that this period is marked by drier conditions (Swindle *et al.*, 2010), while Irish tree-ring records have suggested that a rapid change in climatic conditions occurred between 1,743 cal. yr BP and 1,410 cal. yr BP (Baillie and Munroe, 1988). The results from the C-IT reconstruction show that temperatures notably declined by 0.7 ˚C at 1,800 cal. yr BP and again at 1,650 cal. yr BP. This suggests that cooler temperatures and drier conditions likely occurred in Ireland during the Iron Age Lull and merits further research.

In conclusion, the temperature changes inferred from the Lough Nakeeroge chironomid record are largely in agreement with climate trends and climate events inferred from other palaeoclimate records in Ireland and Europe. This highlights the potential for chironomids to accurately reconstruct broad-scale temperature changes and abrupt temperature events in Ireland throughout the Holocene.

CHAPTER 10: CONCLUSIONS

This research provides valuable evidence for the sensitivity of chironomids to temperature change across various timescales. Correspondence between chironomid-inferred temperature reconstructions and the instrumental records demonstrate the sensitivity of chironomids to small-scale temperature change. Additionally, chironomid response to known catchment changes was still registered in the midge community, which suggests that chironomids could also be used to explore land-use change through time. The ability to differentiate chironomid response to temperature and human impacts exists. However, the complexity in teasing apart the two signals, in the absence of known land-use and meteorological recordings, will pose a challenge for future research.

The importance of careful site selection is highlighted for chironomid-temperature reconstructions in mid-latitude and low-to-mid altitude sites. The diversity of lake types with different chemical, physical, hydromorphological and catchment activities creates a unique chironomid community that may be more responsive to environmental variables other than temperature, such as lake trophic state, pH and lake level (Velle *et al*., 2010a). This study illustrates how complex lake morphology can divorce a chironomid-temperature relationship. Chironomid response to lake level at one of the study sites was clearly identified through changes in terrestrial/semi-terrestrial taxa, which was linked to winter precipitation. Therefore, the potential to reconstruct lake level through time exists using this mechanism and is an area worthy of future exploration.

Appropriate site selection is highly important in chironomid research as basin morphology can control the dominant environmental variables acting on chironomid communities. This study provides information and guidance that could prove useful for the site-selection process of future research projects where the intention is to track past temperature changes using chironomids. Future research should explore chironomid communities' response to physical changes within the lake. This is becoming an important priority in the agendas of Environmental Protection Agencies in Europe, as hydromorphological pressures are now recognised as having a significant impact on the ecological functioning of lakes (Jura *et al*., 2012).

The potential to use chironomid data for lake monitoring in Ireland is an important finding that emerged from the study. The ecological status of Irish lakes is currently monitored by examining the response of macrophytes, phytoplankton and fish-to-nutrient enrichment (Donohue *et al*., 2009; Chen *et al*., 2008; Foy *et al*., 2003) to land-use change and human-induced pollution. While these studies are valuable in ecological monitoring, the role of climate has been largely neglected. Leira *et al*. (2006) highlight that existing research in Ireland does not offer an insight into the sensitivity of lake ecosystems to climate change. As chironomids have been shown to register subtle temperature change in Ireland, there is the potential to use them to reconstruct past climate in order to determine reference conditions against which modern warming can be compared. Furthermore, as chironomids are sensitive to land-use change, these species can be used to monitor both temperature change and human impacts depending on the study location. Therefore, chironomids could potentially be used as early warning systems before ecosystem degradation becomes too great as a result of anthropogenic climate change and nutrient enrichment.

The results of this study stress that known historic changes and archaeological knowledge can be used as ways to gauge the reasons for chironomid change through time. This study used this approach to tease apart a contemporary climate signal from that of a human impact, and suggests that chironomid response to land-use change and climate can be differentiated though time with the use of historical evidence and/or other chemical and biological proxies. Recent evidence has shown that nutrient enrichment from human activities in prehistoric Ireland has a notable effect on the chironomid community from a lake in northwest Ireland (Taylor *et al.*, 2013). Therefore, the importance of differentiating a temperature signal from that of a human impact one is especially important in Ireland, as humans have been a dominant force on the landscape since at least the Neolithic period, 6,000 years ago. Due to the wealth of archaeological and palynological evidence related to human activities along the west of the island, evidence of temperature regimes and land-use change over the Holocene could be used to further investigate human-environmental relations.

The results from this study provided evidence that chironomids are powerful palaeotemperature indicators of Holocene temperature change in Ireland. As this study was exploratory, the potential to examine finer-scale temperature change over the Holocene exists. This would provide a greater insight into temperature change in Ireland. Further research could concentrate on the cooling period between 9,000 cal. yr BP and 7,500 cal. yr BP to determine if the 8,200 yr event is feature of Irish Holocene climate. A notable change in climate was evident in the mid-Holocene form the Lough Nakeeroge C-IT, where temperatures warmed up to 6,000 cal. yr BP and subsequently deteorated until 5,650 cal. yr BP. This time period, the Neolithic, has a rich history of palnological and archaeological evidence that indicates a shift in human activities at this time. However, it is unknown if this change was culturally or climatically driven, and future chironomid research focusing on this time period could provide a useful technique to gauge land-use change in line with changing temperatures over this period. Finally, temperature change in the late-Holocene could also be explored in greater detail, particularly the cooling between 4,000 to 3,600 cal. yr BP and the more abrupt cold phenomenon between 1,800 and 1,650 cal. yr BP. The latter period, known as the Iron Age Lull, has been linked to woodland regeneration as a result of decreased farming activities (Newman et al., 2007; Molloy and O'Connell, 2004; O'Connell, 1994). Future research could use chironomids to identify if this shift in land-use change occurred during this cold event.

Chironomid-temperature reconstructions from multiple sites around the island could generate a robust regional palaeotemperature model for Holocene temperature change in Ireland. There is even the potential to investigate regional variations in Irish Holocene temperatures to gain a deeper understanding of the unique character of Ireland's climate. Ireland's geographical location, on the western fringe of Europe, places the island in an ideal location to potentially assess north Atlantic temperature trends over the Holocene, which could then be compared to temperature reconstructions from more northern latitude oceanic regions, such as Greenland, Iceland and Norway, in order to create a European-scale climate chronology.

Chironomid-temperature research in Ireland is rather limited. Recent research has focused on reconstructing the abrupt shift in temperatures over the late Glacial to early Holocene transition (van Asch *et al.,* 2012; Watson *et al.*, 2010). The findings from this study show the potential for chironomids to be used as palaeotemperate indicators in future research. In addition, this study shows the potential for chironomids to differentiate human and climate impacts on Irish lakes across various timescales. The rich history of human interaction with the Irish landscape and the close association of Irish climate with north Atlantic phenomena makes Ireland an ideal location for chironomid-based palaeolimnological research, and ideal for modern studies of complex human-climate-lake interactions.

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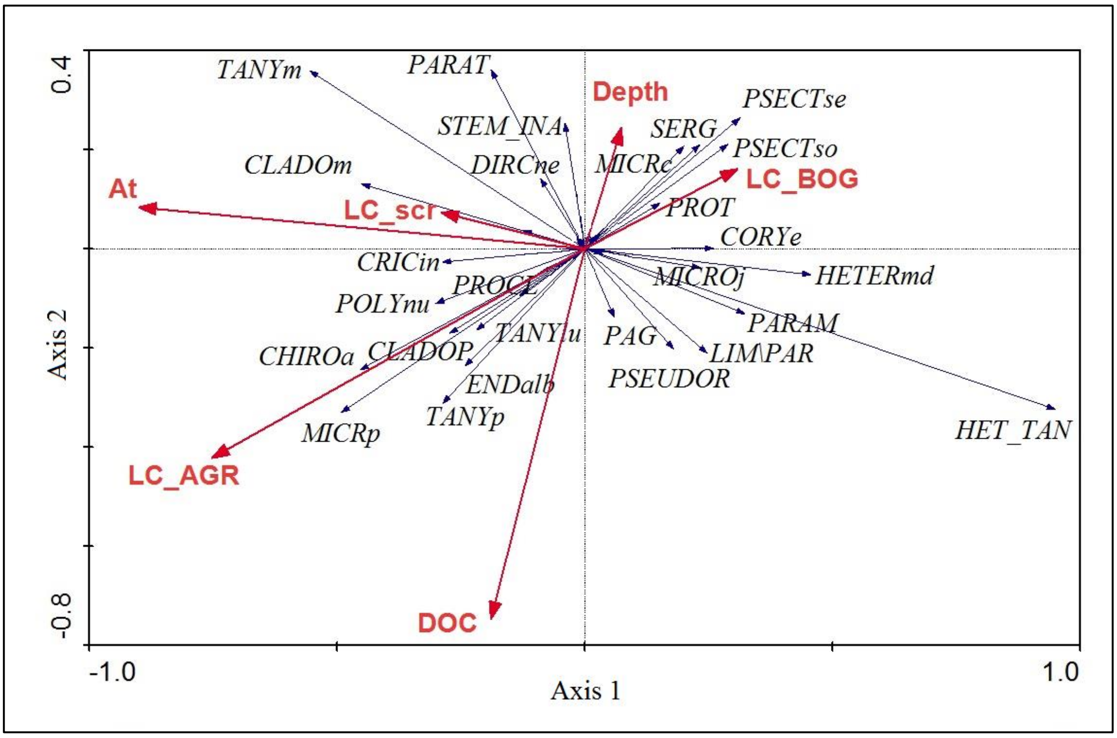
APPENDIX I



Legend

Code name	Taxa full name	Code name	Taxa full name
CHIROa	*Chironomus anthracinus*- type	*PARAM*	*Paramerina*
CLADOm	*Cladotanytarsus mancus*- type	*PARAT*	*Paratanytarsus*
CLADOP	*Cladopelma*	*POLYnu*	*Polypedilum nubifer*- type
CORYe	*Corynoneura edwardsi*- type	*PROCL*	*Procladius*
CRICin	*Cricotopus intersectus*- type	*PROT*	*Protanypus*
DICRne	*Dicrotendipes nervosus*- type	*PSECTse*	*Psectrocladius septentrionalis*- type
ENDalb	*Endochironomus albipennis*- type	*PSECTso*	*Psectrocladius sordidellus/psiloperus*- type
HET_TAN	*Heterotanytarsus*	*PSEUDOR*	*Pseudorthocladius*
HETERmd	*Heterotrissocladius marcidus*- type	*SERG*	*Sergentia*
LIM\PAR	*Limnophyes/Paralimnophyes*	*STEM_ELA*	*Stempellinell/Zavrelia*
MICRp	*Microtendipes pedellus-type*	*TANTlu*	*Tanytarsus lugens*- type
MICROj	*Micropsectra contracta-type*	*TANYm*	*Tanytarsus mendax* -type
MICROj	*Micropsectra junci-type*	*TANYp*	*Tanytarsus pallidicornis*- type
PAG	*Pagastiella*		

Figure A.1. Redundancy analysis (RDA) bi-plots with species scores and environmental variables. Chironomid taxa are listed below bi-plot. *LC_AGR = land cover is agriculture. LC_BOG = land cover is bog. LC_scr = land cover is scrub/grassland. At = Air temperature. DOC = Dissolved Organic Carbon.*