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Chironomid response to prehistoric farming in northwest Ireland

Article-based PhD Thesis

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Discipline of Geography

School of Geography and Archaeology

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Abstract

This article-based PhD thesis explored the utility and performance of chironomid (Diptera: Chironomidae) autecology in the investigation of prehistoric farming impacts on freshwater lake systems. Chironomid subfossils, lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N) and fossil pollen analyses were used in a comparative limnological assessment of three archaeologically rich study sites in County Sligo, Ireland. At all three study sites, pastoral farming and its associated nutrient inputs, as represented by non-arboreal pollen indicative of grassland/pasture (NAPp) and lake sediment geochemistry, were concomitant with increases in eutrophic chironomid taxa. Redundancy analysis (RDA) and partial RDAs established that $\delta^{15}\text{N}$ and NAPp were controlling factors of chironomid community compositional change during the Neolithic (4000 - 2500 BC) and Bronze Age (2500 - 800/750 BC). Bronze Age farming had a considerably greater impact on the lake systems than Neolithic farming, as indicated by a higher proportion of eutrophic taxa and increases in $\delta^{15}\text{N}$, C:N and $\delta^{13}\text{C}$ values, consistent with increased erosion and agricultural inputs. The timing and magnitude of change show that Neolithic and Bronze Age farming exhibited a strong control over chironomid communities at all three sites. Cultural eutrophication also led to the extirpation of several oligotrophic chironomid taxa present in the natural pre-impacted lake systems. In order to verify the importance of prehistoric agricultural influences on the human impacted lakes, an isolated high-elevation catchment was used as a control site to reconstruct chironomid and geochemical response to broad-scale environmental change, where the pollen record showed negligible human activity. Given the lack of prehistoric human influence on the control lake, the record was used to construct the first mid to late Holocene chironomid-inferred temperature (C-IT) record for Ireland, creating a climatic context for the development of Irish society during the Neolithic and Bronze Age. Findings from this PhD thesis provide valuable information about the timing, intensity and environmental impact of prehistoric farming in northwest Ireland.

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List of publications

Below is a list of publications produced in relation to this project.

PhD (2012 - 2017)

Taylor KJ, McGinley S, Potito AP, Molloy K, Beilman DW (2017) A chironomid-inferred temperature record for Irish prehistory from northwest Ireland. (*Under review*) *Palaeogeography, Palaeoclimatology, Palaeoecology*

McGinley S, Taylor KJ (2017) Insights into past environmental and cultural change in Glencolmcille, in: OCarroll E, McClure M (Eds.), South West Donegal, Field Guide No. 34. Irish Quaternary Association (IQUA)

Taylor KJ, Potito AP, Beilman DW, Ghilardi B, O'Connell M (2017) Impact of early prehistoric farming on chironomid communities in northwest Ireland. *Journal of Paleolimnology* 57, 227-244

Taylor KJ, Stolze S, Beilman DW, Potito AP (2017) Response of chironomids to Neolithic land-use change in north-west Ireland. *The Holocene* 27, 879-889

MLitt (2009 - 2011)

Taylor KJ, Potito AP, Beilman DW, Ghilardi B, O'Connell M (2013) Palaeolimnological impacts of early prehistoric farming at Lough Dargan, County Sligo, Ireland. *Journal of Archaeological Science* 40, 3212-3221

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Chapter One - Introduction

1.1. Background and Rationale

Environmental archaeology is continually expanding the range and use of biological proxies in archaeological investigations to provide new information and insights into past societies and the impact of humans on the environment (Murphy and Whitehouse, 2007; Ruiz et al., 2006). Chironomid (Diptera: Chironomidae) subfossils are an excellent biological method for reconstructing past limnological conditions, and recent studies have highlighted the potential for species-specific chironomid autecology in environmental and archaeological contexts (Ruiz et al., 2006; Reuss et al., 2013). Chironomid larvae are extremely sensitive to changes within freshwater lake systems and are ubiquitous in lake environments (Walker, 2001). Although chironomids are traditionally used as palaeotemperature indicators, chironomid communities are affected by a variety of environmental variables including lake pH, lake depth and nutrient status (Eggermont and Heiri, 2012). Stable isotopic analysis of carbon and nitrogen ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) and C:N ratios also offer important information on past limnological conditions, providing information on nutrient loading, lake productivity, sources of lake-sediment organic matter and changing land-use practices (Cohen, 2003; Meyers and Teranes, 2001; Woodward et al., 2012). Both chironomid and geochemical analyses are fully established methods of inquiry in the field of palaeolimnological research. However, few studies combine and utilise these indicators in archaeological contexts.

In Ireland, the first major human impact on the landscape occurred during the Neolithic period (4000 - 2500 BC), with the transition from a hunter-fisher-gatherer society to the introduction of domesticated animals, cereal cultivation, woodland clearance, more permanent settlement and the construction of ritual monuments (Cooney, 2000; Whitehouse et al., 2014). This was followed by an overall intensification of farming activity with metalwork aiding agricultural advancement during the Bronze Age (2500 - 800/750 BC) (Grogan, 2005; Waddell, 2010). Ireland had a prominent Neolithic and Bronze Age, with County Sligo in northwest Ireland having one of the highest concentrations of megalithic tombs in Ireland (Bergh, 1995). Important archaeological sites include the Carrowmore and Carrowkeel-Keshcorran megalithic complexes and the earliest known causewayed enclosure in Britain and Ireland at Magheraboy (Bergh, 1995; Danaher, 2007; Moore, 2004). Given the archaeological significance of County Sligo, it is highly desirable to complement the archaeological findings with a palaeoecological component.

1.2 Research Master of Literature (MLitt)

This PhD is an expansion of my research MLitt completed in 2011, entitled the 'Ecological impacts of early farming in Western Ireland: a palaeolimnological approach' with the findings published in the *Journal of Archaeological Science* in 2013 (Taylor et al., 2013). This study successfully detected the impact of farming activity at one study site, Lough Dargan in County Sligo, using a multi-proxy analysis of a lake sediment core. Chironomid subfossils and lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N ratios) were used to assess changes in limnological conditions through time. The limnological data was compared with macroscopic charcoal concentration and previously published pollen data (Ghilardi and O'Connell, 2013) to examine the potential influence that early farmers had on a freshwater lake system within a prehistorically active catchment. The success of this study demonstrated the effectiveness of a multi-proxy palaeolimnological approach in the investigation of prehistoric farming practices and highlighted the potential for future chironomid-based archaeological research.

1.3 Aim and Objectives

This PhD extends the successful multi-proxy approach of chironomid subfossils, lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N) and pollen analyses to multiple sites in northwest Ireland. The aim of this PhD project is to explore the applicability of chironomid autecology, combined with geochemical indicators in archaeological investigation. Two new sites from County Sligo have been added to the dataset; Templevanny Lough and Lough Cooney, both situated in areas rich in archaeological evidence from the Neolithic and Bronze Age. Results from these additional human impacted sites will provide valuable insights into the human-environmental relations of Neolithic and Bronze Age societies and the development of agriculture in the northwest of Ireland. Palaeolimnological data will offer important information on timing, intensity, location and general environmental impact of prehistoric farming practices in the region.

A lake record from Lough Meenachrinna, located in an isolated catchment in County Donegal, will be included as a control site for the project. Chironomid response from Lough Meenachrinna will be used to further verify the results from the human impacted sites in County Sligo, through comparison of chironomid assemblages in the catchments. As Lough Meenachrinna is a control site, results will potentially provide the first chironomid-inferred temperature (C-IT) estimate for the Irish mid to late Holocene, creating a valuable climatic context for the development of Irish society during the Neolithic and Bronze Age.

1.4 Thesis structure

This article-based thesis is structured in the following manner. Chapter 1 comprises of an introduction to the project including the background and rationale. Chapter 2 consists of a literature review to place the research project amongst key literature and recent developments in the field. The chapter will conclude with four research questions for this PhD project. The general methodological approach will be presented in chapter 3, containing information on the study sites, overall general methodology for the project and explanation of authorship for the three papers.

The first paper of this article-based thesis, 'Response of chironomids to Neolithic land-use change in north-west Ireland' is presented in chapter 4 (Table 1.1). This study provides the first decadal resolved chironomid and organic geochemistry record of the Irish Neolithic from a small lake adjacent to the Carrowkeel-Keshcorran megalithic complex in County Sligo, Ireland. The second paper 'Impact of early prehistoric farming on chironomid communities in northwest Ireland' is presented in chapter 5 (Table 1.1). This study explored the utility and performance of chironomid autecology in the investigation of prehistoric farming impacts on freshwater lake systems in a comparative limnological assessment of three archaeologically rich study sites in northwest Ireland. The final paper is presented in chapter 6, entitled 'A chironomid-inferred temperature record for Irish prehistory from northwest Ireland' (Table 1.1). This study provides the first mid to late Holocene chironomid-inferred temperature (C-IT) model for Ireland, creating a valuable climatic context for the development of Irish society during the Neolithic and Bronze Age. To verify the importance of prehistoric agricultural influences on the human impacted lakes, the isolated, high-elevation catchment will also be used as a 'control' site to reconstruct chironomid and geochemical response to broad-scale environmental change, where the pollen record showed negligible human activity. Numbering for all figures, tables and subheadings for each paper (Chapter 4, 5 and 6) have been altered to create a consistent format through the dissertation for ease of reading. All other content is identical to the journal submissions. Chapters 4, 5 and 6 (and thus all chapters of the dissertation) include their own bibliography.

Chapter 7 identifies common themes through the three papers and explores how the studies can be used together to better understand the impacts of prehistoric land-use and environmental change on chironomid communities in Ireland. The discussion is based around the general research questions presented at the end of chapter 2, and is followed by general conclusions and recommendations for future study.

Table 1.1 - Publication details for the three papers comprising this article-based thesis.

Article-based thesis - Papers				
No.	Lake	Title	Journal	Publication status
1	Templevanny Lough	Response of chironomids to Neolithic land-use change in north-west Ireland	<i>The Holocene</i> (Impact Factor: 2.324)	Article first published online: 3 rd of November 2016; Issue published: June 2017
2	Cooney Lough	Impact of early prehistoric farming on chironomid communities in northwest Ireland	<i>Journal of Paleolimnology</i> (IF: 2.017)	Article first published online: 3 rd of February 2017; Issue published: March 2017
3	Lough Meenachrinna	A chironomid-inferred temperature record for Irish prehistory from northwest Ireland	<i>Palaeogeography, Palaeoclimatology, Palaeoecology</i> (IF: 2.578)	Submitted 15 th of November 2017 for peer review

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Chapter 2 - Theoretical Background

This chapter consists of six sections, providing important background information and critical assessment of the relevant literature for this PhD thesis.

2.1 Palaeolimnology

Palaeolimnology is a branch of palaeoecology that can be defined as ‘the study of past conditions and processes in lake and river basins and the interpretation of the histories of these systems’ (Last and Smol 2001, 1). Lake sediments can provide an uninterrupted chronological record of the past, essentially like a ‘history book’, and are the principal source of data in reconstruction of Quaternary environments. The basis of any palaeolimnological investigation requires a gradual lake sedimentation rate and subsequent formation of a sediment sequence (sediment archive). Small, closed basin lakes are the most suitable for reconstructing past terrestrial environments, as they have the least amount of mixing at the bottom of the lake and offer a simple continuous sedimentation regime (Bennett and Willis, 2001; Bennion et al., 2015).

Palaeolimnological techniques are increasingly being used in the field of environmental archaeology, to inform on human-environment relations (Dearing et al., 2006). Environmental archaeology is concerned with the reconstruction of relationships between past societies and the environments in which they lived. In general, environmental archaeology has a long history of research in Ireland dating back to the seventeenth century (Murphy and Whitehouse, 2007). However, Whitehouse (2007) spotlights the recent addition of insects to environmental archaeology, such as coleoptera and chironomids, to assess past climate and environmental change, as insects are highly sensitive and abundant in both land and freshwater environments. Whitehouse (2007) also emphasises the need for investigation of high resolution sequences of Holocene environmental history in Ireland, to establish overall trends and provide a detailed picture of past societies and environments for archaeological investigation.

2.2 Multi-proxy studies

Multi-proxy studies are becoming increasingly common in palaeolimnological research to more accurately assess the complex interactions and processes that occur within lake systems (Birks and Birks, 2006), both natural and anthropogenic. Birks and Birks (2006, 235) describe a lake ecosystem as an ‘almost infinite network of interactions among biotic and abiotic components balanced between internal and external driving factors’. Abrupt shifts in ecosystem structure and function are often described as ‘regime shifts’, where unexpected and large events occur causing a rapid

ecosystem reconfiguration from one alternative state to another (Lees et al., 2006; Andersen et al., 2009). Regime shifts are well-documented in shallow lakes, and are often associated with anthropogenic eutrophication (Randsalu-Wendrup et al., 2014). In order to understand past ecosystem dynamics, we need to analyse changes in the physical, chemical and biological characteristics of lake sediment records. Due to the complex nature of ecosystem dynamics, it is desirable to incorporate multiple proxies (e.g. pollen, lake sediment geochemistry, chironomid subfossils etc.), to create a more holistic understanding of the system in question (Smol, 2002).

2.3 Proxy indicators

A multi-proxy approach of chironomid subfossils, lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N ratios) and pollen analysis were used to assess chironomid response to prehistoric farming in northwest Ireland for this PhD project. Below is a review of the relevant literature for each proxy indicator.

2.3.1 Chironomid subfossils

Chironomidae belong to a family of true flies (Insecta: Diptera), often referred to as non-biting midges (Brooks et al., 2007; Walker, 2007). Chironomidae are holometabolous insects, meaning they develop from an egg through a series of four larval instars, before pupation leading to final emergence as an adult insect (Brooks et al., 2007; Walker, 2001). Chironomids are ubiquitous in freshwater ecosystems and preserved in Quaternary lake sediments (Brooks et al., 2007; Walker, 2001, 2007). Typically, there can be up to several hundred chironomid head capsules in just a few millilitres of lake sediment (Brooks et al., 2007). The heavily chitinized head capsule of the chironomid is the only feature of the larvae that is resistant to decomposition and can be readily identified to genus and species level (Brooks et al., 2007). There are approximately 1,000 identified European species; however, it is estimated that up to 15,000 may exist in total (Brooks et al., 2007). There are eleven subfamilies within Chironomidae and the six common subfamilies encountered are Tanytopodinae, Chironominae, Tanytarsini, Orthocladiinae, Podonominae, Diamesinae.

As most chironomid larvae develop in freshwater ecosystems (i.e. streams, lakes and rivers), their species composition closely reflects the freshwater environment in which they live (Brooks et al., 2007; Eggermont and Heiri, 2012; Walker 2001, 2007). For this reason, chironomid subfossils have been widely used for palaeoclimatological and palaeoenvironmental reconstructions due to their sensitive nature and susceptibility to changes in limnological conditions (Brodersen and Quinlan, 2006; Brooks and Birks, 2004; Luoto and Salonen, 2010; Ruiz et al., 2006; Velle et al., 2005).

Life cycle characteristics

A detailed overview of the chironomid life cycle is given in Vallenduuk and Moller Pillot (2013) and Brooks et al. (2007) providing detailed descriptions of each stage (Figure 2.1) as follows:

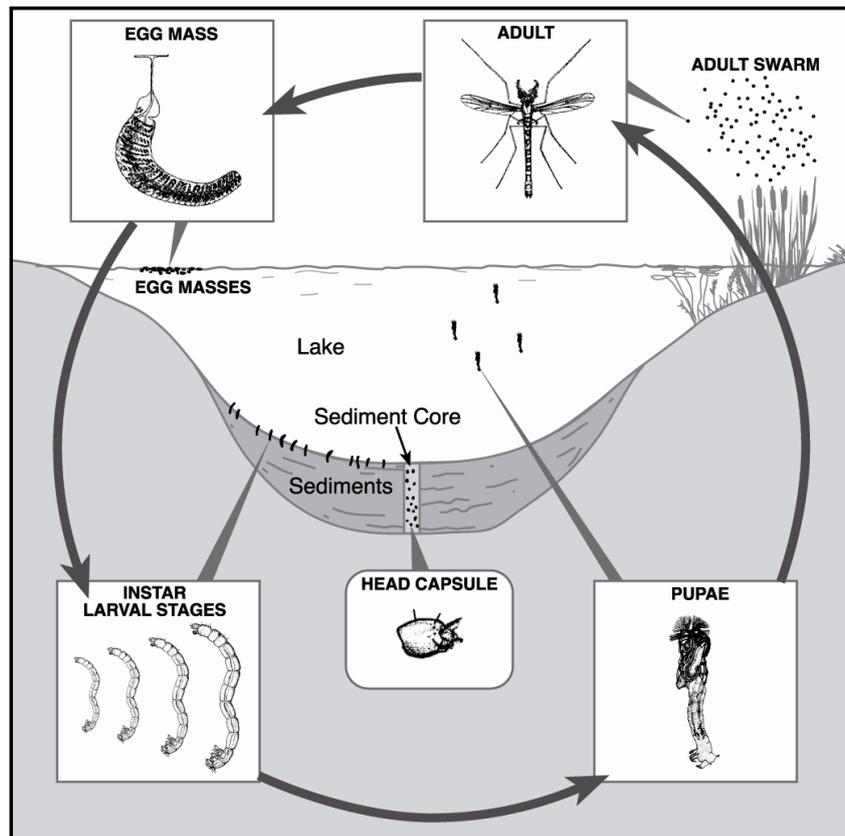


Figure 2.1 - Chironomid lifecycle diagram from Porinchu and MacDonald (2003, 381)

Stage One: Egg - Female chironomidae lay their eggs in a gelatinous matrix, often on a firm substrate such as stones, branches or strong plants along the banks or edges of vegetation. The egg masses float for a short time before absorbing water and sinking (Vallenduuk and Moller Pillot, 2013). Environmental factors such as food availability and ambient temperature dictate the number of eggs produced, while the development of the eggs is temperature dependent and usually takes a few days (Vallenduuk and Moller Pillot, 2013).

Stage Two: Larvae - First instar larvae are morphologically different from later instars with only the shape of the head and the position of the eyes developed (Vallenduuk and Moller Pillot, 2013). The first instar typically ranges between 2 - 8 days. By the second instar, larvae exhibit almost all the species-specific characteristics (morphological, behavioural and autecological) (Vallenduuk and

Moller Pillot, 2013). At the end of each instar, the larvae settle to the bottom and shed their outer chitinous layer including thorax, abdomen and head capsule, and progress to the next stage. Due to differential preservation, the third and fourth instar head capsules shed during ecdysis are most abundant (Walker, 2001). The duration of instars vary widely under the influence of environmental factors, and are largely dependent on temperature and food availability (Vallenduuk and Moller Pillot, 2013). Many species have a diapause in the second, third or fourth instar, which can help the larvae to survive the winter (or summer) so that their active period occurs during the most favourable season (Vallenduuk and Moller Pillot, 2013).

Stage 3: Pupal - The pupal stage is relatively brief, lasting from a couple of hours to days. Timing of emergence is dependent on water temperature and light intensity (Brooks et al., 2007).

Stage 4: Adult - After emergence, adults usually live for less than one day (Brooks et al., 2007; Vallenduuk and Moller Pillot, 2013). Chironomidae fly to mate and deposit eggs and can cover an average distance of 450 m, ranging to a maximum of 3000 m (rare) from their place of emergence (Moller Pillot, 2003). Many species are univoltine (one generation a year), but others may be bi- or trivoltine (Vallenduuk and Moller Pillot, 2013; Walker, 2001).

Chironomids and anthropogenic impact

Chironomidae are traditionally used as palaeotemperature indicators for climatic reconstruction. Distributions of chironomid species/genera, however, can be affected directly and indirectly by a wide variety of environmental variables including lake water pH, lake depth, dissolved oxygen content, benthic substrate morphology and lake nutrient status (Brooks et al., 2007; Brodersen and Quinlan, 2006; Eggermont and Heiri, 2012; Little and Smol, 2001; Potito et al., 2014; Walker, 2001, 2007).

In a recent paper, Reuss et al. (2013) note the great potential for improving the use of chironomid analysis in environmental and climatic studies, with the increasing knowledge of species-specific chironomid autecology. Chironomid autecology, meaning the ecological study of a particular species, has progressed in recent years (Heiri and Lotter, 2003; Langdon et al., 2006; Ruiz et al., 2006; Reuss et al., 2013) with ecological and distributional data for genera and species types through environmental biomonitoring using living and subfossil chironomidae (Luoto and Salonen, 2010). References such as Brooks et al. (2007) Moller Pillot (2009, 2013) Vallenduuk and Moller Pillot (2013) provide excellent information on the distribution and ecology of each taxon, allowing for reconstruction of past limnological conditions.

Vallenduuk and Moller Pillot (2013) highlight that although large quantities of data are available on the presence of chironomids in relation to nutrient enrichment through phosphorus (P) and nitrogen (N) content of the water, there is no direct relationship between these nutrients and the presence of the chironomid larvae. Nutrient loading indirectly impacts the chironomid assemblage through changes in the availability of food (mainly diatoms, organic detritus and macro-invertebrates) and reduced benthic oxygen levels as a consequence of nutrient input (Brooks et al., 2001; Langdon et al., 2006; Vallenduuk and Moller Pillot, 2013).

There are a number of influential palaeoenvironmental investigations which utilise chironomid analysis to assess human-environment relations. Heiri and Lotter (2003) focus on dynamics of chironomid composition over 9000 years at Lake Sägistalsee in the Swiss Alps. The study includes response to long-term climate trends, sensitivity to disturbance and resilience of the chironomids. Results showed that during periods of lower human impact, the catchment vegetation recovers and the chironomid assemblage and abundance reverts to its pre-impacted state. This study highlights the close relationship between human activity in the lake catchment (as reconstructed via terrestrial pollen) and lake fauna. Heiri and Lotter (2003) also noted that the lake's aquatic ecosystem response was exceptionally sensitive to human activity in the catchment area, with minor perturbations having the same effect as major disturbances. Difficulty did arise in separating the influence of climate and human impact, as the largest changes in chironomid-inferred temperature record coincided with periods of intensive human activity in the catchment area.

Francis and Foster (2001) assessed whether the timing, magnitude and nature of lake ecosystem change closely tracked changes in historic land-use intensity and forest cover in three catchment areas in New England. The three small ponds had been subjected to a range of known historical land-use activities including logging, deforestation and agriculture but are at present completely forested. A combination of pollen and historical data was used to investigate changes in terrestrial vegetation, while chironomid analysis was used to assess changes in the aquatic system, along with physical and chemical characteristics of the lake sediment. Results show increased sediment-accumulation rates and small increases in lake productivity (trophic status) at all three sites during periods of settlement. Chironomid taxa indicative of productive aquatic environments (*Chironomus*, *Endochironomus* and *Glyptotendipes*) increased in the post-settlement period. Both the terrestrial and aquatic systems in this study highlight a change in species composition during broad-scale disturbance and do not 'return' to their pre-disturbance composition.

Use of chironomid subfossil analysis has been limited so far in archaeological investigations, however, several papers have noted their potential (O'Brien et al., 2005; Ruiz et al., 2006; Whitehouse, 2007). Ruiz et al. (2006) comprises of three case studies from Britain and Ireland, which

highlight the use chironomid analysis in archaeological investigations. The three case studies include a lake settlement (Ballywillin crannóg) in Lough Kinale, central Ireland; deposits from a Roman well in Northampton; and a floodplain in the East Midlands of Ireland.

Findings from Ballywillin crannóg show increases of *Chironomus plumosus*-type, *Paraphaenocladus* and *Synorthocladus* which indicate an increase in organic detritus, debris and pollution (Ruiz et al., 2006). Also, the presence of *Stenochironomus* (an obligate wood-borer) implies the introduction of some woody substrate and could potentially represent the construction of the Ballywillin crannóg. In the Northampton Roman well deposits, the *Chironomus plumosus*-type head capsules had obvious mouthpart deformities. These deformities have been suggested to reflect sediment pollution by heavy metals, toxic organics and simple organic loading (Janssens de Bisthoven et al., 1995; Lenat, 1993; Reynolds and Ferrington, 2001), possibly indicating a change in the use of the well such as waste disposal. Findings from Ruiz et al. (2006), however are based on a limited number of samples/taxa. Methodologically, use of chironomid analysis should be applied to a more continuous record (i.e. lake sediment core).

A more detailed study of the Ballywillin crannóg affirms the advantages of using a multi-proxy palaeolimnological approach in archaeological investigation (O'Brien et al., 2005). Plant macrofossils, pollen and spores, diatoms, chironomids and coleoptera were used to reconstruct local and regional vegetation change and lake history to establish the age and function of the Ballywillin crannóg. O'Brien et al. (2005) recommend that where possible a multi-proxy approach of sedimentary analysis should be used to provide evidence for nature, use and sequence of site occupation, to replace expensive and potentially destructive excavation in archaeological sites. In the case of previously excavated sites, O'Brien et al. (2005) also acknowledge how palaeoecological analysis could provide complementary data to expand the archaeological database. Both the Ruiz et al. (2006) and O'Brien et al. (2005) showcase the potential for species-specific chironomid autecology, with the use of 'indicator taxa' such as *Stenochironomus* (wood miner), *Gymnometriocnemus* (soil erosion) and *Chironomus plumosus*-type (eutrophic conditions).

The recent use of species-specific chironomid autecology has expanded the utility of this biological proxy for future environmental and archaeological studies. The case studies mentioned above highlight the potential for chironomids to be used as proxy indicators of human activity, providing quantitative data on the character of aquatic environments associated with archaeological sites, as part of a multi proxy approach. By facilitating accurate reconstructions of water quality and substrate in archaeological contexts, chironomids have the potential to provide significant insight into both the changing environmental impact of past societies and the water (and associated) resources available to them (Ruiz et al., 2006).

Chironomids as palaeotemperature indicators

Chironomids are sensitive to lake water and/or ambient air temperature with chironomid community compositions reflecting the environment in which they live (Pery and Garric, 2006; Porinchu and MacDonald, 2003). The temperature of the environment “affects a wide range of physiological and behavioural processes in chironomids including growth and development, respiration and physiological rates, voltinism, emergence, mating and swarming, and swimming behaviour of the larvae” (Eggermont and Heiri 2012, 441). Chironomids are affected both directly and indirectly as temperature also influences lake productivity and in turn food available for the chironomid larvae (Brooks et al., 2007). The principle of temperature dependence enables chironomid subfossils to be used as excellent indicators of past climates and allows for quantitative estimates of past temperature change to be recreated with the help of chironomid-based inference models (transfer functions) (Porinchu and MacDonald, 2003). Chironomid-inferred temperature reconstructions rely on the empirical relationship between the taxonomic composition of chironomid assemblages in lake sediments and air or lake surface water temperature during the summer months (Eggermont and Heiri, 2012). As early as the 1950’s, limnologists such as Brundin (1949) and Thienemann (1954) put forward the idea that temperature may play an important role in determining which chironomid species occur as larvae in lakes. This led to Walker and Mathewes (1989) and Walker et al. (1991) demonstrating that the distribution of subfossil chironomid assemblages in lake surface sediments is strongly related to surface water temperature. Walker et al. (1991) went on to develop the first numerical model (or transfer function) to infer past temperature from fossil chironomid assemblages. Chironomid-temperature inference models have now been developed globally including in arctic, temperate and tropical regions (Heiri et al., 2011; Larocque et al., 2001; Porinchu et al., 2009; Potito et al., 2014), and are well established as palaeotemperature indicators in palaeoenvironmental research.

Heiri et al. (2011) provides the most comprehensive chironomid calibration data-set for temperature reconstruction to date. A dataset of 274 lakes was developed through an amalgamation of two previously published regional calibration sets from Norway and the Swiss Alps (Brooks and Birks, 2001; Heiri and Lotter, 2010). On a more local scale, Potito et al. (2014) provide a systematic assessment of the dominant influences on modern distribution of chironomid subfossils in Ireland, and in doing so created the first Irish training set for July air temperature.

Irish chironomid-inferred temperature reconstructions at present are quite limited, with only three records to date. Watson et al. (2010) was the first Irish chironomid-inferred temperature reconstruction using a lake core from County Donegal. This record covered the lateglacial and early Holocene (LGIT, 15 - 10 ka BP), using a modern Norwegian training set (Brooks and Birks, 2001). van

Asch et al. (2012) provides a reconstruction of the Weichselian late glacial (~14.7 - 11.7 kyr) using a lake sediment core from Fiddaun, County Galway. Lastly, McKeown and Potito (2016) created a temperature reconstruction of the late nineteenth to early twenty-first centuries using the Irish training set (Potito et al., 2014) from two lakes in Northwest Ireland. The study reflected changes in Irish temperature with accelerated warming post-1980. However, the signal became compromised with intensified human impacts in the catchment areas.

Although temperature is considered to be the main driver of chironomid compositional change, several chironomid reconstructions have acknowledged human activity as the main driver behind changes in historic chironomid community composition (Brooks and Birks, 2001; Langdon et al., 2006; McKeown and Potito, 2016). Walker (2007) provides an excellent overview of chironomid research and states that although the natural productivity of lakes and their chironomid communities may be regulated or driven by temperature, human activity can also have major impacts on chironomid community composition.

2.3.2 Geochemistry of lake sediment organic matter

Organic matter comprises an important portion of all lake sediments, originating from “the complex mixture of lipids, carbohydrates, proteins, and other biochemicals produced by organisms that have lived in the lake and its watershed” (Meyers and Lallier-Vergès 1999, 345). Organic matter is therefore derived partly from autochthonous material (organic production within the lake ecosystem) and partly from allochthonous material (the inwash of material from around the lake catchment) (Cohen, 2003). The primary source of organic matter, however, is resultant from particulate detritus of plants (Meyers and Lallier-Vergès, 1999). Sources of plant material can be divided into two geochemically distinctive groups based on their biochemical compositions: (1) non-vascular plants, low in carbon-rich cellulose and lignin (e.g. phytoplankton), and (2) vascular plants, which contain large proportions of these fibrous tissues (e.g. emergent macrophytes in lakes, grasses, shrubs and trees within the lake’s catchment) (Meyers, 2003; Meyers and Lallier-Vergès, 1999; Meyers and Teranes, 2001). Stable isotopic analysis is based on the principle that plants retain these source distinctions (Meyers and Teranes, 2001). Therefore, isotopic analysis of the lake sediment organic matter can reflect the environmental conditions in and around a water body that existed at the time of their accumulation (Routh et al., 2004).

Lake systems are diverse and the sources, alterations and degradation of organic matter are geographically and temporally variable (Meyers and Teranes, 2001). For example, microbial reworking of organic matter components occurs during the deposition of sediment, which strongly reduces the total amount of organic matter and replaces many of the primary compounds with

secondary ones (Meyers and Lallier-Vergès, 1999; Meyers and Teranes, 2001). Despite the generally low survival rate for most primary organic compounds, various organic matter components of lake sediment retain source information, allowing for the reconstruction of limnological and climatological records using generalizations about the geochemical characteristics of organic matter present.

C:N ratios

In general, proportions of sedimentary organic matter that originate from aquatic sources, as opposed to terrestrial sources, can be distinguished by the characteristic C:N ratio composition of algae and vascular plants. C:N ratios are typically calculated as the mass ratio of organic carbon to total nitrogen elemental concentrations. Fresh organic matter from phytoplankton reveal C:N ratios that are commonly between 4 - 10, whereas vascular plant material from land (and the exception of emergent macrophytes in lakes) produce C:N ratios of ≥ 20 (Meyers, 2003; Meyers and Teranes, 2001). The difference in C:N ratios is characterised by protein content. Organic matter high in algae, phytoplankton and zooplankton have a high protein content producing low C:N ratios, whereas terrestrial plants have a low protein content, generating high C:N ratios (Routh et al., 2004). In terms of application in palaeolimnological reconstruction, C:N ratios have commonly been used to infer changes in productivity (trophic status) within a lake system (Brenner et al., 1999; Routh et al., 2004).

Organic carbon stable isotopes

Analysis of the carbon stable isotopic composition ($\delta^{13}\text{C}$) of organic matter in limnological studies helps to provide information on organic matter sources, past productivity rates and allows for identification of changes in the availability of nutrients in surface waters (Meyers and Teranes, 2001). Although the bulk $\delta^{13}\text{C}$ composition can be identified for specific plants (Huang et al., 1999; Gebauer and Meyer, 2003; Cloern et al., 2002), the interpretation of $\delta^{13}\text{C}$ values from lake sediments is not a straight-forward process. The principal determinants of sediment $\delta^{13}\text{C}$ values are 1) the rate of carbon uptake during algal productivity and 2) the dissolved inorganic carbon (DIC) isotopic composition. Meyers and Teranes (2001, 247) also note that “changes in pH, temperature, nutrient limitation, and growth rate are also known to affect the $\delta^{13}\text{C}$ of organic matter produced by phytoplankton”. Despite the complexity of the $\delta^{13}\text{C}$ as a proxy, many studies have successfully used $\delta^{13}\text{C}$ to interpret past environments including Brenner et al. (1999), Diefendorf et al. (2008) and Mackie et al. (2005).

Nitrogen stable isotopes

The nitrogen stable isotopic signature ($\delta^{15}\text{N}$) of sediment is another powerful tool in limnological reconstruction. $\delta^{15}\text{N}$ sediment signature is a complex indicator with many possible interpretations, such as to identify the dominant source of nitrogen (N) to lakes, the influence of internal microbial cycling or changes in lake productivity (Botrel et al., 2014; Cohen, 2003; Meyers and Teranes, 2001). Nitrogen enters the lake in different ways. Taken together with internal lake processes, this makes interpretation challenging at times. Nitrogen concentrations also differ considerably between terrestrial and aquatic plants. Terrestrial plants (vascular) with woody tissue and cellulose have relatively low concentrations of N, whereas phytoplankton (non-vascular) low in cellulose are rich in N. This differentiation can sometimes allow for identification of changes in the past availability of nitrogen to aquatic primary producers. Most often the $\delta^{15}\text{N}$ of bulk sediment organic matter is used to reconstruct past changes in N source, with inferences based on the principle that each N source has a distinctive $\delta^{15}\text{N}$ signature (Botrel et al., 2014). For example, human-derived N typically has a high $\delta^{15}\text{N}$ composition; the $\delta^{15}\text{N}$ signal of human and animal wastes ranges between +10 and +20‰. Synthetic fertilizer, however, have a low $\delta^{15}\text{N}$ of between -4 and +4‰. Atmospheric N has a $\delta^{15}\text{N}$ signal of -15 to 15‰ for dissolved inorganic N (DIN) in wet deposition (Kendall et al., 2007), and the majority of soils have a $\delta^{15}\text{N}$ signal of between 2 - 5‰ (Kendall, 1998). Using these distinct signatures, several studies have attempted to track different N sources coming from waste water (Leavitt et al., 2006), agricultural organic or inorganic fertilizers (Bunting et al., 2007) and atmospheric deposition (Jones et al., 2004; Holtgrieve et al., 2011) as compiled in Botrel et al. (2014). Given the multiple factors that may influence nitrogen values in lake sediment, it is recommended in Botrel et al. (2014) that analysis of sedimentary $\delta^{15}\text{N}$ be accompanied with other proxies such as aquatic pollen in a multi-proxy approach.

Woodward et al. (2012) used statistical analysis to assess factors controlling lake surface sediment $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ from 50 lakes in western Ireland, spanning a human-impact gradient. Results showed that surface sediment $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ depended on the origin of the lake sediment organic matter, whether it was composed mostly from allochthonous or autochthonous material. Woodward et al. (2012) showed that agricultural inputs were a major influence on $\delta^{15}\text{N}$ values in surface sediments of modern Irish lakes. In agriculturally active catchments, greater $\delta^{15}\text{N}$ values were found in concert with a decrease in $\delta^{13}\text{C}$ values, inferring high $\delta^{15}\text{N}$ values may be indicative of animal husbandry. Lakes in less impacted catchments (<20% agricultural land cover within the catchment) had a mean $\delta^{15}\text{N}$ value of 2.6‰, moderately impacted catchments (20 - 80% agricultural cover) show an increased $\delta^{15}\text{N}$ mean value of 3.7‰ and in highly-impacted catchments (>80% agricultural cover) mean $\delta^{15}\text{N}$ values further increased to 5.1‰ (Woodward et al., 2012).

Stable isotopic analysis has also been used to indicate soil erosion through in-wash of allochthonous material. Alin et al. (2002) used isotopic analysis of carbon and nitrogen to highlight a historical relationship between watershed land-use and aquatic biodiversity. This study showed that $\delta^{15}\text{N}$ enrichment was accelerated by watershed flooding and erosion events, affecting both lake productivity and biodiversity.

2.3.3 Pollen analysis

Palynology is the study of plant pollen, spores and other remains (termed 'palynomorphs') in both living and fossil form. Analysis of fossil pollen is one of the principal techniques used in palaeolimnology (Bennett and Willis, 2001; Moore et al., 1991). A typical pollen grain consists of 1) the central portion (living part) surrounded by a cellulose case known as the 'intine', which does not survive in the fossil form; 2) the outer layer ('exine'), consisting of a resistant, waxy coat of material called 'sporopollenin'. The exine protects the inner reproductive section and is preserved well in sediments allowing for identification (Lowe and Walker, 2015). Pollen grains are typically elliptical or spherical in shape and can vary in diameter from 10 - 100 μm . The spores of ferns and mosses are different from pollen in structure, but fall within the same size range (Bennett and Willis, 2001). Identification is carried out by examining the features on the surface of the pollen grain (exine), such as number and location of apertures and nature of sculpturing, along with shape and size of the pollen grain itself (Bennett and Willis, 2001; Beug, 2004; Moore et al., 1991). Pollen is typically identified to genus or family level but within some groups may be possible to species level. Pollen grains are ubiquitous in a variety of sediment types, in particular fresh water lakes and peatland deposits, and are readily preserved in these anaerobic conditions. Different plant taxa disperse pollen in different ways; most pollen is dispersed by wind (anemophilous) or by insect (entomophilous) (Bennett and Willis, 2001; Proctor et al., 1996). Plants that disperse pollen by wind tend to produce more pollen than plants that produce insect-dispersed pollen (Bennett and Willis, 2001), both accumulating on the ground surface or in water bodies (Lowe and Walker, 2015). This is important to take into account in interpretation of results, as pollen records cannot be assumed as having a one to one relationship.

A systematic analysis of pollen throughout a lake sediment core is highly beneficial to any palaeolimnological reconstruction, as pollen counts provide 'a measure of the vegetation composition around the site of accumulation at the time of accumulation' (Bennett and Willis 2001, 24), thus providing valuable information about past environmental change. For over a century, palynology has been used to determine past vegetation dynamics through time (Bennett and Willis, 2001; Lowe and Walker, 2015). Initially, pollen analysis was used to infer climate (von Post, 1946),

but more recently the technique has been used to study human impact on the landscape, successional change and other biotic and abiotic factors (Bennett and Willis, 2001). In Ireland, the first Irish pollen diagram was published by Gunnar Erdtman in the Irish Naturalists' Journal in 1927 (Mitchell et al., 2013). Mitchell et al. (2013) have compiled over 475 pollen diagrams from locations throughout Ireland with a range of sites and time frames in the Irish Pollen Site Database (IPOL), available at www.ipol.ie. This data has been used to reconstruct vegetation dynamics over long timescales in the investigation of climate change, plant migration and human impact (Mitchell et al., 2013).

Human impact has been the dominant factor affecting vegetational change since the beginning of the Irish Neolithic period (Lowe and Walker, 2015; O'Connell and Molloy, 2001). Many Irish studies have used pollen analysis to assess the impact and evolution of our cultural landscape during the mid to late Holocene (Edwards and Hiron, 1984; Ghilardi and O'Connell, 2013; Molloy and O'Connell, 2004; O'Connell and Molloy, 2001; Overland and O'Connell, 2008; Plunkett, 2009; Stolze et al., 2013; Verill and Tipping, 2010). Human activity during the Neolithic and Bronze Age has left a clear imprint in pollen records, with widespread woodland clearance, farming (pastoral and arable) and the introduction of new plant species into regions. This imprint is particularly evident in sites rich in archaeological evidence, including County Sligo. In many pollen records, woodland was cleared to facilitate both arable and pastoral farming. This is reflected not only by reduced frequencies of arboreal pollen, but also by increases in pollen associated with grassland/pasture and cereal cultivation (Molloy and O'Connell, 2004; O'Connell and Molloy, 2001). These pollen signals are commonly referred to as 'anthropogenic indicators' (Behre, 1986). *Plantago lanceolata* (ribwort plantain) is one of the main pollen types primarily used as an indicator of pastoral farming in Europe as it plays a significant role in the recolonization of abandoned cultivated land (Behre 1981). *Plantago lanceolata* is normally included in a group of non-arboreal pollen indicative of grassland/pasture (NAPp), including taxa such as Liguliflorae (dandelion), *Ranunculus acris*-type (buttercup), *Rumex acetosa*-type (sorrel) and Cyperaceae (grasses) (Figure 2.2; Behre (1981)). Arable pollen groupings usually include taxa such as cereal-type pollen, *Hordeum*-type (barley), *Triticum* (wheat) and Chenopodiaceae (goosefoot family) (Behre, 1981).

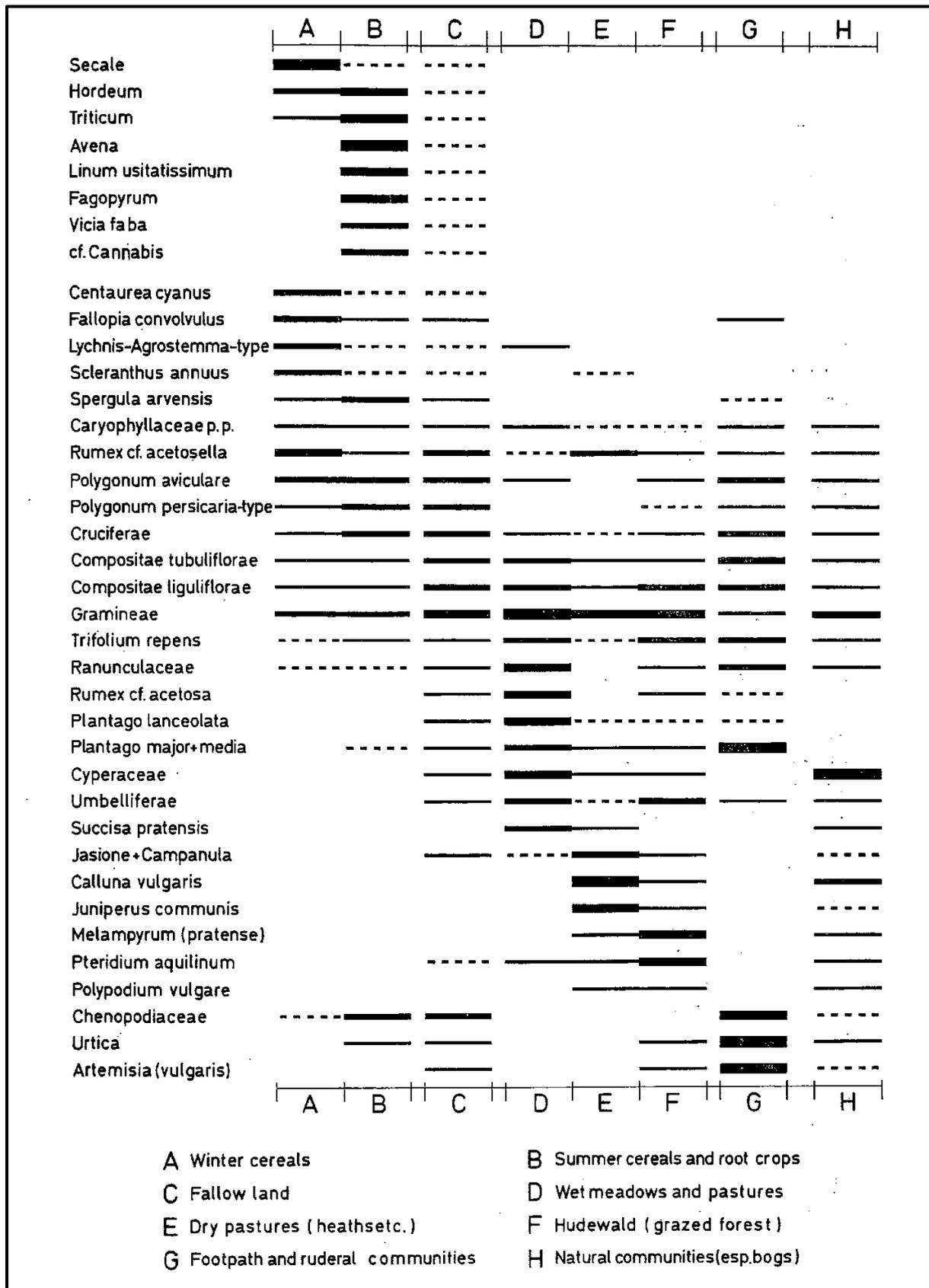


Figure 2.2 - 'Anthropogenic indicators' (Behre 1981, 233)

'Non-pollen palynomorphs' are also included in pollen counts. Three important non-pollen palynomorphs at one study site in this project, Lough Meenachrinna were aquatic algae *Pediastrum*, *Isoetes* and *Botryococcus*. Aquatics can be used to inform on trophic state and soil erosion/inwash of material. For example, *Botryococcus* (a green planktonic microalga) can be used in the interpretation of lake trophic state, as *Botryococcus braunii* is found in abundance in 'dystrophic' acidic brown water lakes and is most commonly recorded in shallow, partly saline lake systems (Tyson, 2012; Warren, 1986). High *Isoetes* representation in lake sediment can reflect erosion/sediment in-wash events (Vuorela, 1980). Lastly, high *Pediastrum* representation in pollen profiles has been associated with nutrient-rich lakes (Cohen, 2003), in particular with epilimnetic productivity likely reflecting large algal blooms (Komarek and Jankovská, 2001; Weckström et al., 2010).

Charcoal particles (>37 µm) can also be included in the grouping non-pollen palynomorphs. Charcoal particles are frequently found in lake sediments and generally reflect fire activity both natural (forest fire) and human-related (from cooking sites '*fulacht fia*' and woodland clearance) (Whitlock and Larsen, 2001). Charcoal particles are visually recognizable as opaque, angular and usually planar, black fragments (Whitlock and Larsen, 2001). Since the work of Iversen (1941), charcoal data has been used to examine the linkages among climate, vegetation, fire and anthropogenic activities in the past (MacDonald et al., 1991; Whitlock and Larsen, 2001). Charcoal can be categorised as 1) macroscopic (particle size classified as >100 µm in size) which reflect local fire activity and 2) microscopic (>37 µm) providing a more regional fire signal (Whitlock and Larsen, 2001). The addition of charcoal counts in pollen analysis can be a useful tool, especially in comparison with levels of NAPp and arable pollen in studies of prehistoric human impacts on the landscape (Chique et al., 2017; Ghilardi and O'Connell, 2013; O'Connell and Molloy, 2001).

2.4 Trophic status and impact of farming activity on lake environments

Lakes can be characterised by their primary biological productivity and divided into three main classifications: oligotrophic (low level of productivity), mesotrophic (intermediate level of productivity) or eutrophic (high level of productivity). The natural balance of a lake system can often be altered by anthropogenic nutrient enrichment (i.e. cultural eutrophication). Lake systems are nutrient-limited systems and particularly limited in nitrogen and phosphorus. In a modern context, human activities such as the disposal of human and animal waste, burning of fossil fuels and the use of artificial fertilisers in agriculture, have led to eutrophication of lake environments (Davidson and Jeppesen, 2013). Agriculture, in particular, is one of the major sources of phosphorus and nitrogen to aquatic ecosystems (Carpenter et al., 1998). Cultural eutrophication through nutrient enrichment is caused by the inputs of nutrients either directly to lakes or indirectly through inflowing rivers and/or

streams (Brodersen and Quinlan, 2006). The high nutrient loading frequently leads to increased production of macrophytes, epiphytic and planktonic microalgae, turbid water, excessive blooms of often toxic cyanobacteria and loss of biodiversity (Brodersen and Quinlan, 2006; Davidson and Jeppesen, 2013). In pastoral areas for example, phosphorus and nitrogen from manure accumulate in the surrounding catchment soils and can be an important driver of nutrient input. Nutrient-rich soils are deposited into the lake system, where some of the phosphorus dissolves and stimulates growth of aquatic plants and phytoplankton. Within-lake recycling of nutrients from sediments and consumers can then act to enhance eutrophication through time resulting in changes in trophic status (Carpenter et al., 1998; Carpenter, 2005).

The main human impacts on lake environments during the Neolithic and Bronze Age in Ireland were pastoral and arable farming activities and soil erosion from woodland clearance. According to pollen records (Ghilardi and O'Connell, 2013; Molloy and O'Connell, 1995; O'Connell et al., 2014), and compound-specific carbon isotope analysis of pottery vessels (Smyth and Evershed, 2015), Neolithic farming in western Ireland was predominantly pastoral, with evidence of Neolithic cattle dairying in the County Sligo. In a multi-disciplinary review of the Neolithic period, Whitehouse et al. (2014) suggest that arable farming was also present during the Neolithic in Ireland, and likely consisted of the cultivation of small permanent plots of mostly wheat and barley. Arable farming became more intensive during the Bronze Age as evidenced in a number of Irish pollen records (Ghilardi and O'Connell, 2013; O'Connell et al., 2014). Little is known, however, about the impact of these activities, particularly on freshwater lake systems.

In the reconstruction of human impact on lake systems, Brodersen and Quinlan (2006) highlight the importance of assessing the natural, pre-disturbance conditions of a lake system in order to fully understand culturally induced change. Lake sediment analysis provides unique insights into the history of freshwater ecosystems, offering evidence for the nature and timing of ecosystem change (Bennion et al., 2015). Davidson and Jeppesen (2013) note in the last 20 years, the application of palaeolimnological approaches for tracking and assessing eutrophication has greatly increased.

2.5 Research questions

A multi-proxy palaeolimnological approach of chironomid subfossil, lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N) and pollen analyses will be used to address the following research questions:

1) Can palaeolimnological indicators be used as a proxy for a regional prehistoric farming signal through biotic and geochemical analyses of multiple lake sediment cores?

Following on from this general research question, was prehistoric farming extensive enough during the Neolithic and Bronze Age to impact multiple freshwater lakes in County Sligo? And, is there a predominance of a particular type of farming impacting lake systems, i.e. pastoral and/or arable? These questions will be assessed through general ecological interpretations of chironomid and geochemical analyses, which will be compared with land-use data from existing and new pollen records from each study site. Interpretation will include statistical analysis of the palaeoenvironmental proxy data from three human impacted sites (Lough Dargan, Templevanny Lough and Cooney Lough, County Sligo) and a control site (Lough Meenachrinna, County Donegal).

2) Are chironomids sufficiently sensitive to reflect scale of farming activity?

If prehistoric farming sufficiently impacted the additional study sites of Templevanny Lough and Cooney Lough, can chironomids be used to indicate degree of environmental impact during the Neolithic and Bronze Age? This will be assessed through comparison of chironomid assemblage data with the lake sediment geochemistry and pollen records at each site, using ordinations to infer environmental controls on chironomid compositional change. Chironomid assemblages should show a greater response to intensified Bronze Age farming, although a simple on/off response to human activity is also possible (Heiri and Lotter, 2003). The addition of the control site will help to determine if catchment land-use is primarily responsible for evident changes within the chironomid communities rather than any regional controls such as climate. Sampling for chironomid and geochemical analyses was completed at the same depth as the pollen samples for this PhD to optimise comparability between proxies.

3) Can regular chironomid taxa be identified in response to prehistoric farming, for use in future investigations?

The potential for species-specific chironomid autecology, using modern ecological and distributional data for chironomid genera and species type, in environmental and archaeological contexts has recently been highlighted with the concept of 'indicator taxa' (O'Brien et al., 2005; Reuss et al., 2013; Ruiz et al., 2006). This will be assessed through comparison of chironomid assemblages across the

three impacted sites - Lough Dargan, Templevanny Lough and Cooney Lough. Identification of indicator taxa will provide greater efficiency and cohesiveness in future investigations in the region.

4) In an isolated catchment in northwest Ireland, can chironomid analysis infer past changes in Irish summer temperature? Furthermore, can a human impact signal be separated from a temperature signal to create a chironomid-inferred temperature estimate?

Considering Ireland's relatively dense human settlement and active farming since the Neolithic period (Cooney, 2000; Whitehouse et al., 2014), it may prove difficult to locate an isolated catchment uninfluenced by human activity during the Neolithic and Bronze Age to infer past temperature. By implementing a multi-proxy approach of chironomids, lake geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N) and pollen analyses at a high elevation, isolated site, any potential limnological impact from human activity in the region can be ascertained. Lough Meenachrinna will act as a control site, particularly for the chironomid and geochemical portion of this study. Differences in chironomid community composition will be highlighted between an un-impacted catchment, and three human impacted catchments in County Sligo, during the Neolithic and Bronze Age.

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Chapter Three - Study sites and methodology approach

3.1 Study region - Archaeology of County Sligo

County Sligo was chosen as the study region as it was an important and densely populated area of settlement during the Neolithic and Bronze Age, based on the abundance of archaeological evidence from this time period. County Sligo has the highest density of megalithic tombs in Ireland (Bergh, 1995). According to the Archaeological Survey Database (www.archaeology.ie) there are 64 court, 77 passage, 11 portal, 37 wedge and 47 unclassified megalithic tombs located within the county alone. There are two main areas rich in archaeological evidence from Neolithic period: the Cúil Irra peninsula, west of Sligo town; and the Bricklieve Mountains and Hill of Keshcorran, in south County Sligo (Figure 3.1).

One of Ireland's four megalithic complexes is located on the Cúil Irra Peninsula, namely the Carrowmore megalithic complex, and holds the greatest concentration of passage tombs in Ireland (Bergh, 1995; Bergh and Hensey, 2013). The Cúil Irra Peninsula is a projection of land extending from Strandhill to Slieve Deane, surrounded by bays to the north and south and Lough Gill forming an eastern boundary. The Carrowmore complex is comprised of roughly 60 passage tombs, datable to the Neolithic period (Bergh, 1995; Bergh and Hensey, 2013). There are three main distributions of megalithic monuments on the peninsula. The first is the cluster of seven monuments on the summit of Knocknarea, which is dominated by the great cairn known as *Miosgán Meabha* (Bergh, 1995; Bergh, 2002). The huge unopened cairn is surrounded by six satellite monuments and overlooks the second densely clustered group of passage tombs, situated in the lowlands of Carrowmore in the centre of the Cúil Irra Peninsula. Carrowmore consists of c. 30 remaining monuments; it is originally thought to include a total of 60 monuments. The third distribution is located on Carns Hill on the eastern end of the peninsula, comprising of two large cairns. In close proximity to Carns Hill is the early causewayed enclosure at Magheraboy, which has yielded some of the earliest AMS ¹⁴C dates for the Neolithic in Ireland and Britain (Danaher, 2007; Cooney et al., 2011). Additionally, there are several megalithic monuments scattered across the Ox Mountains, Slieve Deane and within the peninsula itself both on high and low ground. Chronologically, the small passage tombs at Carrowmore lie within 4500 - 3500 BC, with *Miosgán Meabha* likely contemporaneous with Newgrange and Knowth (Bergh, 1995; Bergh, 2002) of the internationally renowned archaeological complex of *Brú na Bóinne* in County Meath (Hensey, 2015; Lynch, 2014). *Brú na Bóinne* was most likely constructed between 3200 and 3000 BC (Lynch, 2014). The most intensive period of use at Carrowmore is thought to be between 3600 - 3200 BC (Bergh and Hensey, 2013).

The Carrowkeel-Keshcorran complex is the second major passage tomb complex in Ireland and is located on the summit plateaus of the Bricklieve Mountains and Hill of Keshcorran, County Sligo. It is one of the less understood complexes in Ireland (Hensey et al., 2013), with a series of some 20 passage tombs spread across the upland landscape (Bergh, 1995; Moore, 2004). A cluster of 153 hut sites is located on the limestone plateau of Mullaghfarna at the eastern side of the Bricklieve Mountains (Bergh, 2006). Use of the monuments and activity at the Carrowkeel-Keshcorran complex is dated from the middle Neolithic to the middle Bronze Age (Hensey et al., 2013). The most recent dating evidence has raised the possibility that Carrowkeel cairns were in use as early as c. 3500 BC, several hundred years before Newgrange (Hensey, 2015). It is clearly apparent that County Sligo was an important and populated area during the Neolithic and Bronze Age based on ample archaeological evidence.

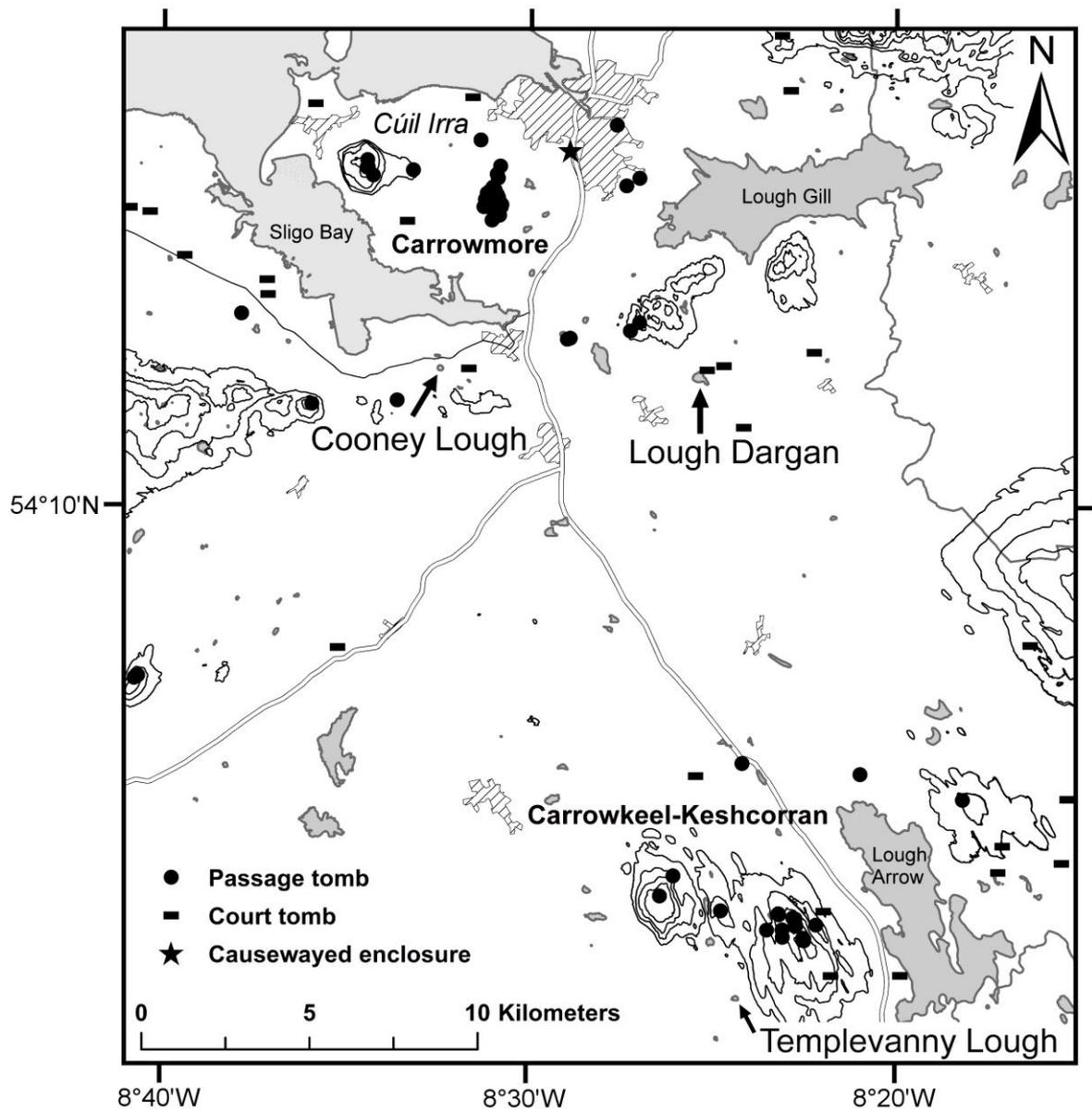


Figure 3.1 - Map of County Sligo with location of Lough Dargan, Cooney Lough and Templevanny Lough in relation to the Carrowmore and Carrowkeel-Keshcorran megalithic complexes.

3.2 Expansion of methodological approach from previous (MLitt) research

Lough Dargan was the original human impacted lake for this project. The multi-proxy approach of chironomids, geochemical and pollen analyses were proven to be an effective tool for investigating prehistoric human impacts on a freshwater lake. This study offered a unique insight into Neolithic and Bronze Age farming practices in County Sligo, including scale and intensity of farming and the relative impacts of pastoral and arable farming on a freshwater lake. Results from Lough Dargan were published in Taylor et al. (2013).

Lough Dargan was a collaborative project with Professor Michael O’Connell and Dr Beatrice Ghilardi of the Palaeoenvironmental Research Unit (PRU), National University of Ireland Galway (NUIG) and Dr David Beilman of the University of Hawai’i at Mānoa. I was responsible for the chironomid analysis and the preparation of samples for lake sediment geochemistry aspect of this project, which complemented the pollen analysis that had been previously published (Ghilardi and O’Connell, 2013). See Appendix 1 for abstract of Taylor et al. (2013).

Subsequently, the methodology has been expanded to multiple study sites for this PhD thesis. The overall methodological plan for this project is to include two additional human impacted study sites from County Sligo and a control site from County Donegal (Figure 3.2 and Table 3.1). The two additional human impacted sites, Templevanny Lough and Cooney Lough, will be used to create a regional picture of the potential environmental impact of prehistoric farming. Both additional sites are located in areas rich in archaeological evidence from the Neolithic and Bronze Age, see figure 3.1. The control site, Lough Meenachrinna in County Donegal, will be used to verify the palaeolimnological results from the human impacted sites, and will provide a palaeolimnological record relatively free from direct human impacts. Lough Dargan has also been incorporated into Paper 2 of this PhD thesis as a comparative human impacted site, with new statistical analysis (redundancy analysis - RDA) completed using the Lough Dargan data.

The below table provides a breakdown of study sites, number of samples, time frame and the purpose of each lake (Table 3.1).

Table 3.1 - Details of study sites from MLitt and PhD theses

Lake	No. of samples	Time frame	Purpose
Lough Dargan (MLitt)	67	5690 - 730 BC	Human impact; previously published
Templevanny Lough	160	4120 - 2480 BC	Human impact; Paper 1
Cooney Lough	77	5290 - 805 BC	Human impact; Paper 2 (comparative)
Lough Meenachrinna	67	5065 - 105 BC	Climate; Paper 3

3.2.1 Study sites

1. Human impacted lake (MLitt) - Lough Dargan

Lough Dargan (54°12.113'N, 08°25.461'W) is situated east of Collooney and immediately to the south of a low, east-west running range of hills, an outlier of the Ox Mountains (Figure 3.1 and 3.2). Lough Dargan is a medium-sized lake of 10 ha and 11.2 m maximum depth, which lies in a sheltered, closed basin at 45 m above sea level (Ghilardi and O'Connell, 2013). A small stream enters at the north-western end of the lake, and nearby there is a small outflowing stream. The lake was originally chosen on account of the rich-archaeological evidence located in the surrounding catchment area (see Taylor et al., 2013). The Carrowmore megalithic complex and Magheraboy are roughly 8 km northwest of Lough Dargan. The four large cairns on the Ox Mountains that overlook Lough Dargan lie within 2-2.5 km of the lake. There are also several megalithic tombs in the lowlands around the lake, including four court tombs and a portal tomb (details in Ghilardi and O'Connell, 2013). Both tomb types relate to the early Neolithic. Wedge tombs, datable to the early Bronze Age, are also common in the area, as are standing stones and burnt mounds (including *fulacht fia*) that are primarily indicative of Bronze Age activity (Danaher, 2007; Ghilardi and O'Connell, 2013).

2. Human impacted lake - Templevanny Lough

Templevanny Lough (54°2.100'N, 08°24.350'W) is a small oval-shaped lake (2 ha) located at an elevation of 84 m a.s.l. in the south-eastern Ballymote Lowlands, County Sligo (Figure 3.1 and 3.2). The lake has a number of minor inflows and a stream that drains to the south-west. Templevanny Lough was chosen on account of its location, due to its close proximity to the Carrowkeel-Keshcorran megalithic complex providing evidence of human settlement during the Neolithic and Bronze Age (Appendix 2.1).

3. Human impacted lake - Cooney Lough

Cooney Lough (54°12.13'N, 8°32.28'W) is situated approximately 2 km west of Ballysadare, County Sligo, on a lowland coastal strip between Ballysadare Bay and the Ox Mountains (Figure 3.1 and 3.2). It is a small lake (2.5 ha) of moderate depth (maximum = 8.3 m), which lies at an elevation of 36 m above sea level. The study site was chosen on account of its rich archaeological evidence from the Neolithic and Bronze Age (Appendix 2.2). Carrowmore megalithic complex is located on Cúil Irra peninsula and approximately 4 km north of Cooney Lough. Several archaeological sites also lie in

close proximity (~2.5 km) to the lake including a court tomb, passage tomb and *fulacht fia* (O'Connell et al., 2014).

4. Control site - Lough Meenachrinna

Lough Meenachrinna (54°43'41.8"N, 8°40'45.5"W) is located in the *Chruach an Chuilinn* mountains, 4 km northeast of the village of *Gleann Cholm Cille* (Glencolmcille), County Donegal (Figure 3.2 and Appendix 2.3). It is a small (3.6 ha), high elevation (286 m a.s.l.) lake, with a maximum of water depth of 7.3 m. The lake is situated on the Precambrian, Slieve Tooley Quartzite formation (Geological Survey of Ireland, 2013), and the surrounding catchment vegetation is dominated by blanket bog and heathland. Lough Meenachrinna was chosen as the control site for this project on account of its remote upland location, along the northwestern edge of Ireland. The immediate lake catchment shows no archaeological evidence of human activity from the Neolithic to Iron Age.

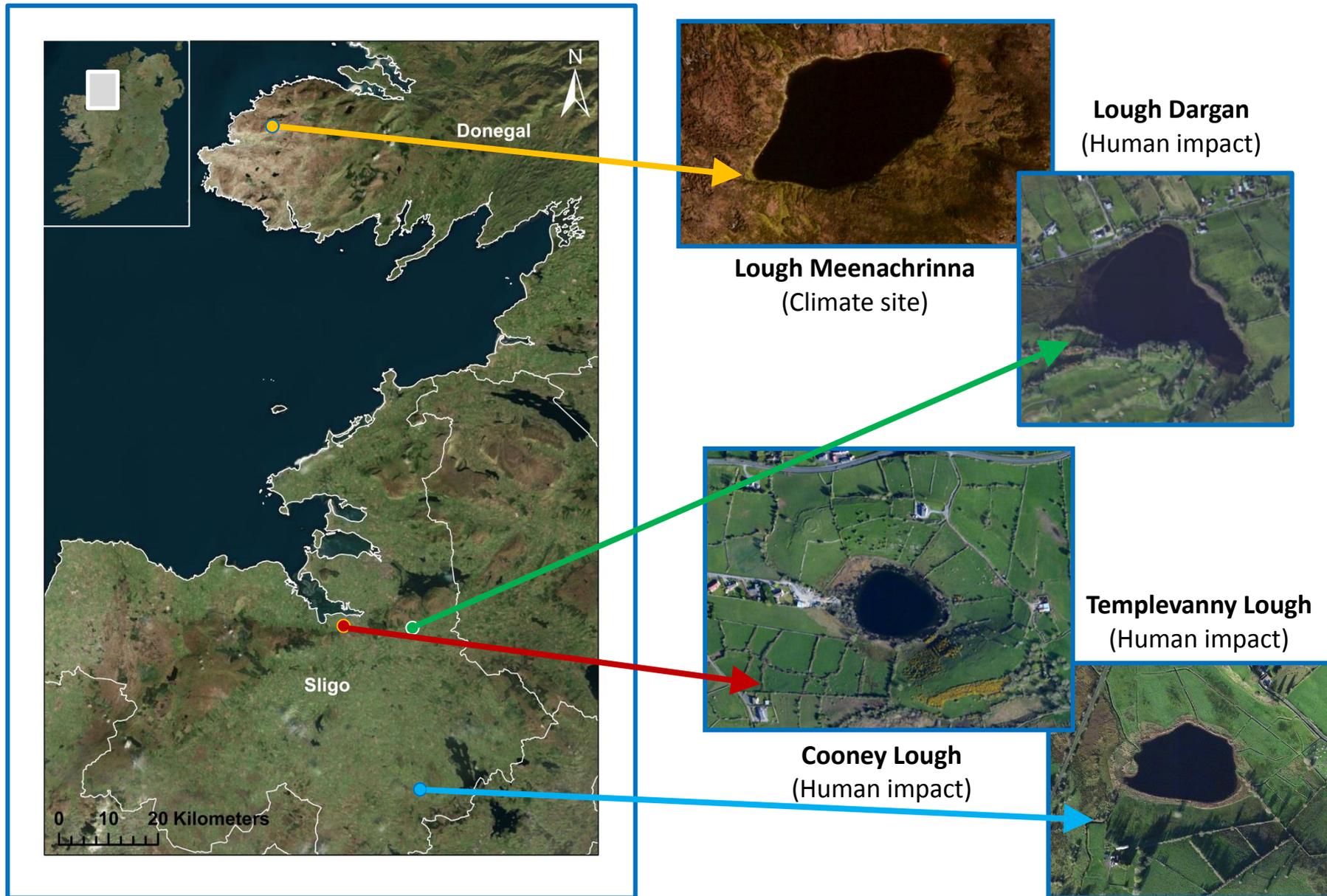


Figure 3.2 - Study sites

3.3 Methodological approach for human impacted sites

The first article focuses on Templevanny Lough, County Sligo. This lake was part of a collaborative project with Dr Susann Stolze of the National Oceanic and Atmospheric Administration, Boulder, Colorado and Dr David Beilman (Table 3.2). The aim of the first paper (Taylor et al., 2017b) was to provide the first reconstruction of lake response to anthropogenic activity at a decadal resolution of the Neolithic in Ireland, using chironomid subfossils, lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N ratios), macroscopic charcoal and a new extended pollen stratigraphy.

The second article is based on the work from Cooney Lough, County Sligo. This paper was a collaboration with Professor Michael O'Connell, Dr Beatrice Ghilardi and Dr David Beilman (Table 3.2). The aim of the second paper (Taylor et al., 2017a), was to explore the capabilities of chironomid analysis, combined with geochemical ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N) indicators, to investigate the environmental impacts of Neolithic and Bronze Age farming across the region. The first part of this paper reports the new palaeoenvironmental findings from Cooney Lough. The second part of the paper provides a comparative limnological assessment from the findings of the three human impacted sites - Lough Dargan, Templevanny Lough and Cooney Lough - using constrained ordinations to explore regional trends from the dataset.

The two additional sites, Templevanny Lough and Cooney Lough, were previously cored in 2008 and 2010, respectively. Dating models, pollen and loss-on-ignition (LOI) analyses were previously completed and published in Stolze et al. (2013) and O'Connell et al. (2014), respectively. The Templevanny Lough core was subsampled by Dr Susann Stolze at Kiel University, Germany. A total number of 160 samples were subsampled spanning the Neolithic period (4120 - 2480 BC) at 1-cm intervals. I subsampled the Lough Cooney core (CNY1 and CNY2) at the PRU, with a total number 77 samples spanning the late Mesolithic to the end of the Bronze Age (5290 - 805 BC) at 1 to 4-cm intervals. For this PhD, subsampling for chironomid and stable isotopic analyses were taken at the same depths as the previously published pollen analyses to improve comparability and interpretation (this was not possible for the Lough Dargan core). For Templevanny Lough in particular, the sampling resolution was greatly increased to decadal resolution in comparison with the relatively low resolution of the Lough Dargan study. I completed the chironomid extraction and identification, and lake sediment geochemistry preparation of all samples at each lake. Dr David Beilman completed the stable isotopic analysis of carbon and nitrogen for the lake sediment samples for both lakes. Multivariate statistical analysis, including principal component analysis (PCA) and redundancy analysis (RDA) were performed for each lake to determine the main environmental controls on the chironomid compositional change. I completed the data analysis, interpretation of results, write up of manuscripts and submission to journals, with guidance and support from my

supervisor Dr Aaron Potito. Dr Susann Stolze and Prof Michael O'Connell both provided input to their respective papers. See table 3.2 for further details on the contribution to authorship and content. Details on the methodology of each proxy are specified in the papers - see chapters 4 and 5.

3.4 Methodological approach for Lough Meenachrinna (Control site)

Lough Meenachrinna, County Donegal, was chosen as the control site for this PhD project. It is a collaborative study with Dr. Karen Molloy and Seamus McGinley of the PRU and Dr David Beilman (Table 3.2). The aim of the third paper was to create the first independent chironomid-inferred temperature record for the mid to late Holocene in Ireland, using a lake sediment core from an isolated catchment in northwest Ireland. This study will create a valuable climatic context for the development of Irish society during the Neolithic and Bronze Age, and will also act as an effective 'control' site of chironomid compositional change independent of significant human impacts.

Lough Meenachrinna was cored in the summer of 2013 by myself, Dr Aaron Potito, Dr Carlos Chique and Seamus McGinley. The subsequent core, DL-LM-B was subsampled at NUIG with a total number of 67 samples at 1-cm intervals for chironomid, lake sediment geochemistry and pollen analyses. Ten samples were submitted for AMS ^{14}C dating to the ^{14}C CHRONO Centre, Queen's University Belfast. I completed the chironomid extraction (samples 132 - 65 cm) and identification (samples 132 - 55 cm), lake sediment geochemistry preparation and loss-on-ignition (LOI) portion of the project. Seamus McGinley completed the remaining chironomid extraction samples (samples 64 - 55 cm) and the sand percentage analysis for the DL-LM-B core. I completed the pollen sample preparation and identification for 33 samples (132 - 66 cm). Dr Karen Molloy completed the remaining samples (64 - 54 cm) for the project. Dr David Beilman completed the stable isotopic and elemental analysis of carbon and nitrogen for the lake sediment samples. Multivariate statistical analysis, including principal component analysis (PCA) and redundancy analysis (RDA) were completed for this lake to determine the main environmental controls on chironomid compositional change. I completed the data analysis, interpretation of results, write up of the research article and submission to the journal, with guidance and support from my supervisor Dr Aaron Potito and Dr Karen Molloy. See table 3.2 for further details on the contribution to authorship and content. Details on the methodology of each proxy are again specified in the paper - see chapter 6.

Table 3.2 - Contribution to authorship and content for PhD thesis

Paper 1 (Templevanny Lough): Response of chironomids to Neolithic land-use change in north-west Ireland				
Paper 2 (Cooney Lough): Impact of early prehistoric farming on chironomid communities in northwest Ireland				
Paper 3 (Lough Meenachrinna): A chironomid-inferred temperature record for Irish prehistory from northwest Ireland				
<i>Aspects of paper</i>		Paper 1	Paper 2	Paper 3
Coring		Stolze et al. (2013)	O'Connell et al. (2014)	KT, AP, SG
Subsampling		SS	KT	KT
Obtaining radiocarbon dates (14Chrono Centre, Belfast)		Stolze et al. (2013)	O'Connell et al. (2014)	KT, KM
Creation of dating model		Stolze et al. (2013)	O'Connell et al. (2014)	KT
Chironomid analysis	Chironomid extraction	KT	KT	KT (samples 132 - 65 cm) SG (samples 64 - 54 cm)
	Identification of samples	KT	KT	KT
Stable isotopic analysis	Preparation of samples	KT	KT	KT
	Processing of samples	DB	DB	DB
Loss-on-ignition (LOI) analysis		Stolze et al. (2013)	O'Connell et al. (2014)	KT
Pollen analysis	Preparation and processing of samples	Stolze et al. (2013)	O'Connell et al. (2014)	KT, KM
		SS - addition of 32 new samples		
	Identification of samples	Stolze et al. (2013)	O'Connell et al. (2014)	KT (samples 132 - 66 cm) KM (samples 64 - 54 cm)
Sand percentage analysis		N/A	N/A	SG
Data analysis and creation of figures		KT	KT	KT
Interpretation of results		KT, AP	KT, AP	KT, AP, KM
Write up of manuscript		KT (main author), AP, SS	KT (main author), AP, MOC	KT (main author), AP, KM

Legend: Karen Taylor = KT, Aaron Potito = AP, David Beilman = DB, Karen Molloy = KM, Michael O'Connell = MOC, Susann Stolze = SS, Beatrice Ghilardi = BG, Seamus McGinley = SG

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Chapter 4 - Paper One

“Response of chironomids to Neolithic land-use change in northwest Ireland”

Response of chironomids to Neolithic land-use change in northwest Ireland

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4.1 Abstract

This study provides the first decadal-resolved chironomid and organic geochemistry record of the Irish Neolithic from a small lake adjacent to the Carrowkeel-Keshcorran complex in County Sligo, Ireland. Chironomid (non-biting midge fly) subfossils and lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N) from the Templevanny Lough core were used to assess the timing and magnitude of within-lake responses to Neolithic farming activity. When compared with decadal-resolved pollen and macroscopic charcoal records from the same core, the limnological data show a direct influence of prehistoric farming on a freshwater lake system through nutrient loading and lake eutrophication. Elevated nutrient levels, suggesting a more productive lake system, and a subsequent turnover in the chironomid community indicate a period of intensive farming activity from c. 3790 - 3620 BC in the early Neolithic. This was followed by a decline in farming with short periods of small-scale human activity, exemplified through nutrient loading and short-lived increases in eutrophic chironomid taxa during the middle to late Neolithic. A return of farming activity can be seen in all proxy data in the late Neolithic (c. 2720 - 2480 BC). The chironomid community composition typically lagged land-use change by c. 10 - 20 years, and exhibited predictable and proportional responses to agricultural activity. The timing and magnitude of limnological changes show that land-use, rather than climate, is the main control on chironomids at Templevanny Lough, thus showing the potential prominence of the anthropogenic signal during the Neolithic.

Keywords

Palaeolimnology, Neolithic, chironomids, geochemistry, lake response, Ireland

4.2 Introduction

The Neolithic period in Ireland (c. 4000 - 2500 BC; cf. Cooney, 2000) coincides with the first widespread evidence of substantial human impacts on the landscape (Waddell, 2010). The transition from hunter-fisher-gatherer Mesolithic societies to Neolithic farming-based economies saw the arrival of domesticated animals, grain cultivation, woodland clearance and more permanent settlement (Cooney, 2000). Northwestern Ireland, and particularly County Sligo, had an especially prominent Neolithic, including one of the highest concentrations of megalithic tombs in Ireland (Bergh, 1995) and the large passage tomb complexes of Carrowmore and Carrowkeel-Keshcorran.

Neolithic cultivation is typified by small, permanent plots of mostly wheat and barley, best described as intensive garden agriculture (Whitehouse et al., 2014). Neolithic farming also saw the introduction of cattle, pig, and sheep/goat, with cattle dairying becoming especially prominent across the region (Smyth and Evershed, 2015). These activities have been shown to enhance soil erosion rates and increase nutrient loading through both farming activities such as tillage and trampling and increased deposition of animal waste (Taylor et al., 2013). Palaeolimnological data can provide insights on human-environment relationships through time (Heiri and Lotter, 2003), including degree of environmental degradation, scale and intensity of farming activity or proximity of farming to a lakeside.

Chironomid analysis is a powerful tool in limnological reconstruction, as chironomid larvae are extremely sensitive to lake conditions (Walker, 2001). Due to their susceptibility to changing environmental conditions and frequent abundance in freshwater lake systems, chironomids have been increasingly used in palaeoenvironmental reconstructions to qualitatively assess past land-use change and its impact on the environment (O'Brien et al., 2005; Ruiz et al., 2006; Taylor et al., 2013). Geochemical indicators ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N) have been applied to complement chironomid analysis, as they provide information on lake productivity, sources of lake-sediment organic matter and changing land-use practices (Cohen, 2003; Woodward et al., 2012). The combination of these proxies with pollen and macroscopic charcoal data allows for a systematic investigation into the limnological impacts of prehistoric human activities. This methodology proved successful at Lough Dargan, County Sligo, where close linkages were established between human land-use and lake eutrophication, with farming and associated nutrient loading being the main influences on the chironomid community during the Neolithic and Bronze Age (Taylor et al., 2013). However, a low sampling resolution and staggered sub-sampling did not permit a detailed investigation of magnitude and timing of lake response to land-use change.

The aim of this study is to provide a high-resolution assessment of the timing and intensity of Neolithic land-use and its impact on Templevanny Lough, a small lake adjacent to the Carrowkeel-

Keshcorran complex, County Sligo (Figure 4.1). Present knowledge of the Carrowkeel-Keshcorran complex and prehistoric landscape change derives mainly from archaeological and pollen investigations (Bergh, 1995; Göransson, 1984, 2002; Hensey et al., 2013; McAulay and Watts, 1961; Mitchell, 1951; Mount, 1996; Stolze, 2012; Stolze et al., 2012, 2013a,b). This paper provides the first reconstruction of lake response to anthropogenic activity at a decadal resolution of the Neolithic in Ireland, using chironomid subfossils, lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N ratios), macroscopic charcoal and a new extended pollen stratigraphy.

4.3 Study Site

The study site is situated in the south-eastern Ballymote Lowlands, County Sligo. Carboniferous limestone forms the bedrock which is overlain by glacial deposits (MacDermot et al., 1996). Templevanny Lough (54°2.100'N, 08°24.350'W) is a small oval-shaped lake of approximately 2 ha in size located at an elevation of 84 meters above sea level (Figure 4.1). The lake has a number of minor inflows and a stream that drains to the southwest. Templevanny Lough is bordered by farmland. The Bricklieve Mountains are located approximately 1 km to the north-east of the study site.

The Carrowkeel-Keshcorran complex is one of the four major passage tomb complexes of Ireland and is located on the summit plateaus of the Bricklieve Mountains and hill of Keshcorran. It is one of the less thoroughly studied complexes in Ireland (Hensey et al., 2013), with a series of some twenty passage tombs spread across the upland landscape (Bergh, 1995; Moore, 2004). A cluster of 153 hut sites is located on the limestone plateau of Mullaghfarna at the eastern side of the Bricklieve Mountains (Bergh, 2006). Use of the monuments and activity at the Carrowkeel-Keshcorran complex is dated from the middle Neolithic to the middle Bronze Age (Hensey et al., 2013). The most recent dating evidence has raised the possibility that Carrowkeel cairns were in use as early as c. 3500 BC, several hundred years before Newgrange (Hensey, 2015). The passage tomb of Newgrange is part of the internationally renowned archaeological complex of Brú na Bóinne in County Meath (Lynch, 2014; Hensey, 2015), and was most likely constructed between 3200 - 3000 BC (Lynch, 2014).

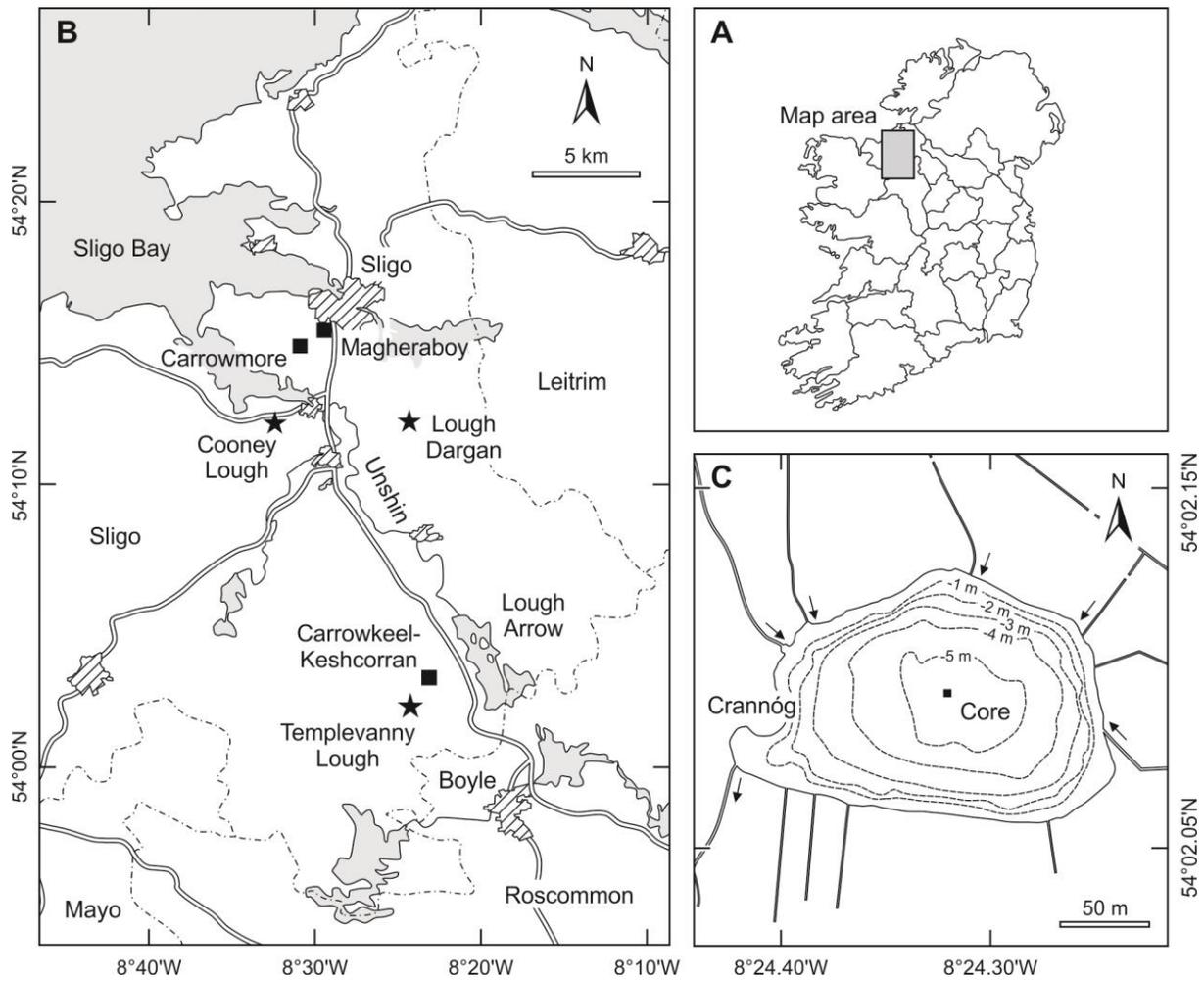


Figure 4.1 - Maps showing the study region in northwest Ireland (A) and County Sligo with locations of Neolithic archaeological sites, previously investigated lakes and Templevanny Lough, studied in this contribution (B). Map (C) illustrates the study site showing minor inflow and outflows and the location of a crannóg within the Templevanny Lough catchment. The coring location is indicated.

4.4 Methodology

4.4.1 Coring and sub-sampling

Two parallel 13 m-long cores were extracted using a Usinger piston corer, at a water depth of 6 m close to the centre of Templevanny Lough in 2008 (Stolze et al., 2013b). The sediment interval between 999.5 - 839.5 cm was contiguously sampled at 1-cm resolution for chironomid, geochemical, macroscopic charcoal and pollen analyses.

4.4.2 Radiocarbon dating

Age control for Templevanny Lough is based on sixteen ^{14}C -AMS determinations from Stolze et al. (2013b). An additional six dates were obtained for this study using terrestrial plant material retrieved from the sediments (Stolze et al., in preparation). The sediment samples were treated with 10% HCl and rinsed with deionized water through a 125- μm sieve. The plant material was picked under a stereo microscope. Radiocarbon dating was performed at the 14CHRONO Centre, Queen's University Belfast. A new depositional model was calculated for the 160 cm-long sediment sequence with the program OxCal 4.2 (Bronk Ramsey, 1995, 2001, 2009), applying the INTCAL13 curve (Reimer et al., 2013). Calculation of the Poisson depositional model was performed at 0.5-cm increments and a number of events per unit length of 10 cm^{-1} . Boundaries were set at 975.5 cm and 897.5 cm. Outlier analysis was performed and identified six of the 22 samples as not reliable. Ages obtained by Bayesian age-depth modelling are expressed as the mean of the posterior probability distributions and rounded to the nearest 10 years. The 95.4% highest probability density intervals are used as a measure of uncertainty of this age estimate, which range from 25 to 85 years, with a median value of 40 years.

4.4.3 Chironomid analysis

Chironomid analysis followed standard procedures outlined by Walker (2001). Between 0.75 and 4.5 cm^3 of sediment was deflocculated in a 10% KOH solution and heated at 30°C for 30 minutes. The sediment slurry was sieved through a 90 μm mesh, and the sieve residue was poured into a Bogorov plankton counting tray to be sorted at 10 - 40x magnification using a Motic[®] SMZ Series dissection microscope. A minimum of 50 head capsules per sample were removed with forceps and permanently mounted on slides with Entellan[®] for identification. Chironomid identifications were made using a Motic[®] B3 Professional Series compound microscope at 100 - 400 x magnification. Taxa were identified to genus, sub-genus or species level following Brooks et al. (2007), Larocque-Tobler

(2014), Rieradevall and Brooks (2001) and Wiederholm (1983). Chironomid ecology and distribution information are based on Brooks et al. (2007), Moller Pillot (2009, 2013) and Vallenduuk and Moller Pillot (2007).

For presentation purposes, chironomid types associated with rivers and streams were grouped together in the chironomid stratigraphy. Total stream taxa include *Corynoneura lobata*-type, *Epoicocladius*, *Euryhopsis*, *Heleniella*, *Krenosmittia*, *Paracricotopus*, *Parametriocnemus/Paraphaenocladius*, *Paratrissocladius*, *Stilocladius*, *Rheocricotopus* undifferentiated, *Rheocricotopus chalybeatus*-type, *Rheocricotopus effusus*-type, *Rheocricotopus fuscipes*-type and *Thienemanniella clavicornis*-type.

4.4.4 Geochemical analyses ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N)

All contiguous samples were analysed for stable isotope ratios of nitrogen and organic carbon ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$) and the elemental concentrations of C and N. Sediment samples of 1 cm³ were dried, pulverized with a mortar and pestle, and passed through a 200 μm sieve. Between 2 and 5 mg of homogenized material was weighed into silver capsules and HCl-fumigated following Harris et al. (2001) and measured for $\delta^{13}\text{C}$ values. A separate analysis was conducted to measure $\delta^{15}\text{N}$ values of a non-acidified portion of the samples. Stable isotope ratios of C and N were determined using a Thermo Fisher Delta V Advantage EA-IRMS at the Isotope Biogeochemistry Laboratory, University of Hawai'i at Mānoa. C:N was calculated from organic carbon and total nitrogen elemental concentrations. Isotope ratios are reported as ‰ relative to the Vienna PeeDee Belemnite (VPDB) standard and atmospheric nitrogen for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, respectively. Accuracy, i.e. the offset between measurements and standards, for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, was $\pm 0.3\text{‰}$.

4.4.5 Macroscopic charcoal analysis

For all 160 samples, macroscopic charcoal particles ($\geq 90 \mu\text{m}$) were counted in concert with the chironomid extraction and charcoal accumulation rates (particles cm⁻²yr⁻¹) were determined.

4.4.6 Loss-on-ignition and pollen analyses

To provide a complete pollen and geochemical record for the Neolithic period from Templevanny Lough, the previously published loss-on-ignition and pollen stratigraphies (Stolze et al., 2013b) were each complemented by the analysis of 32 additional sediment samples taken between 870.5 and 839.5 cm. Detailed preparation protocols for both analyses are given in Stolze et al. (2013b). The organic (LOI₅₅₀) and inorganic carbon (LOI₉₅₀) contents determined at 550°C and at 950°C (Heiri et al.,

2001) as well as the non-combustible fraction (NCF) are presented here. In the present contribution, a percentage curve summarising pollen types largely indicative of grassland communities (cf. Behre, 1981; Brun, 2011) and the arboreal pollen curve are displayed. These pastoral pollen indicators (PPI) include *Cirsium*, Tubuliflorae, Lactucaae, *Plantago lanceolata* type, Poaceae: wild grass group, *Rumex acetosa* type, *Plantago major-media* type, *Ranunculus* type and *Trifolium* type. In addition, the *Plantago lanceolata* type curve is shown. Due to the nearly consistent occurrence of *Hordeum* type pollen in the pollen stratigraphy, possibly reflecting the presence of *Glyceria* on the lake fringe rather than the cultivation of *Hordeum* (cf. Stolze et al., 2012), this pollen type is not considered as an anthropogenic indicator here. Calculation of the pollen percentages is based on the terrestrial pollen and spore sum.

4.4.7 Statistical analyses

Ordination analyses were performed using Canoco version 4.54 (ter Braak and Šmilauer, 2006) on square-root transformed chironomid percentage data for all common taxa, i.e. taxa present in at least two samples with a relative abundance of $\geq 2\%$ in at least one sample (Quinlan and Smol, 2001). Both principal component analysis (PCA) and detrended correspondence analysis (DCA) were carried out. PCA results were used as this analysis gave a better overall explanation of the variance in the data. Redundancy analysis (RDA), a constrained linear ordination technique, was performed to identify which of the environmental variables could explain a statistically significant ($p < 0.05$) amount of the variance in the chironomid dataset. The statistical significance of each variable was assessed using Monte Carlo permutation tests (499 unrestricted permutations). A series of partial RDAs was completed for six environmental variables (PPI, *Plantago lanceolata* type, macroscopic charcoal, C:N, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$) to determine which of the variables retained high explanatory importance for chironomid distribution.

The chironomid percentage diagram was constructed using C2 version 1.7.6 (Juggins, 2014), and zonation was performed on the percentage data of all taxa using ZONE version 1.2 (Juggins, 1992). Zonation was based on optimal sum-of-squares partitioning and statistical significance of zones was determined using BSTICK (cf. Bennett, 1996). All other graphs and linear regressions were completed using SigmaPlot version 12.0.

4.5 Results

The multi-proxy record from Templevanny Lough spans the time interval from c. 4120 - 2480 BC (999.5 - 839.5 cm), covering the Irish Neolithic. In the following, the down-core variations of the chironomid and other proxy data are presented (Figures 4.2 - 4.5).

4.5.1 Chironomid stratigraphy and zonation

Four statistically significant zones were determined. The sub-division of Zone 4 is not statistically significant, but was included here as the sub-zonation shows a note-worthy qualitative change within the chironomid community. Fifty to 82.5 chironomid head capsules (mean = 56) were identified per sample. A total of 126 distinct taxa were identified in the Templevanny Lough core, with 19 to 40 different taxa (mean = 29) per sample.

Zone 1 = c. 4120 - 3790 BC (999.5 - 973.5 cm). The chironomid taxa dominating Zone 1 are *Chironomus anthracinus*-type, *Tanytarsus mendax*-type and *Corynoneura lobata*-type (Figure 4.2). *Chironomus anthracinus*-type abundance is relatively high at ~12% in the beginning and end of Zone 1. Its dip in abundance in the middle of this zone, coincides with a dip in the total chironomid concentration. *Tanytarsus mendax*-type abundance increases from 5 - 17% between c. 3810 - 3800 BC (975 - 974 cm). *Tanytarsus lugens*-type emerges at 6% abundance at c. 3800 BC (974 cm). There is an increase in *Corynoneura lobata*-type from 0 - 12% between c. 3970 - 3930 BC (988 - 985 cm), with levels of ~7% for the remainder of this zone. *Cladopelma* and *Microtendipes pedellus*-type occur in the lower half of the zone. While *Microtendipes pedellus*-type remains present at a lower abundance in the upper portion of this zone, *Cladopelma* disappears at c. 3930 BC (985 cm).

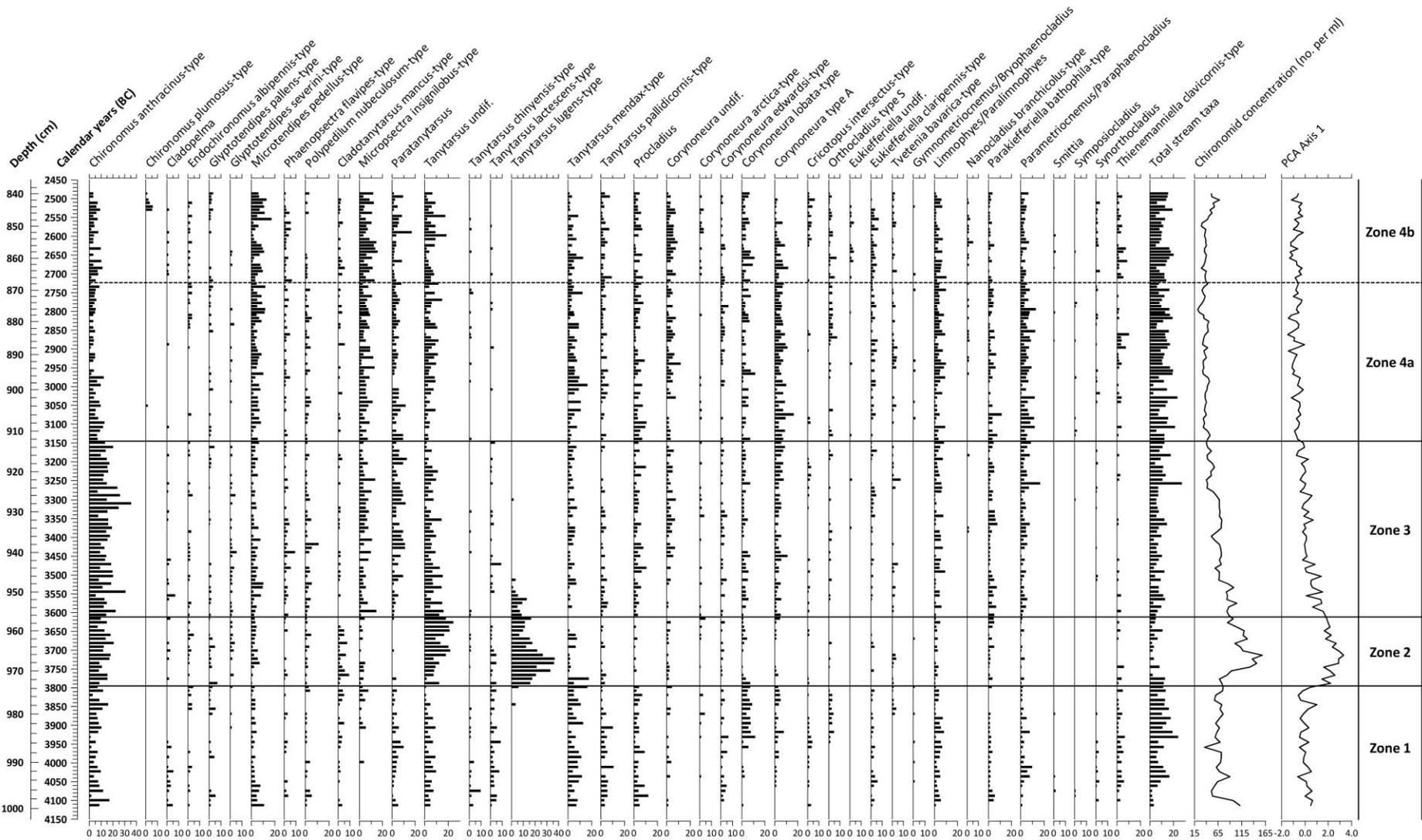


Figure 4.2 - Chironomid percentage diagram from Templevanny Lough, Co. Sligo, arranged by subfamily.

Zone 2 = c. 3790 - 3610 BC (973.5 - 956.5 cm). A noteworthy shift in the chironomid community composition is recorded from Zone 1 to Zone 2. *Tanytarsus lugens*-type dominates this zone, with an average of 26% between c. 3790 - 3720 BC (973 - 967 cm) and a peak of 33% at c. 3760 BC (970 cm). *T. lugens*-type decreases toward the end of this zone, with an average of 11% from c. 3660 - 3620 BC (961 - 957 cm). *Chironomus anthracinus*-type and *Tanytarsus* undifferentiated (undif.) show higher values than in Zone 1 and exhibit an increasing trend throughout this zone. The largest sample-to-sample increases in *Chironomus anthracinus*-type (8%) are found at c. 3720 BC (967 cm) and c. 3680 BC (963 cm). *Corynoneura lobata*-type, *Corynoneura* type A, *Paratanytarsus*, *Procladius* and total stream taxa become less abundant in Zone 2. PCA axis 1 ($\lambda=0.113$) supports the noted shift in the chironomid community composition (Figure 4.3a). The species bi-plot shows a strong relationship between PPI, *P. lanceolata* type and *T. lugens*-type, with *T. lugens*-type appearing to the extreme right of the taxa bi-plot (Figure 4.3b). The highest chironomid concentrations of 159 head capsules per cm³ are observed in this zone (Figure 4.2).

Figure 4.3 - Environmental variables - macroscopic charcoal, pastoral pollen indicators (PPI), *Plantago lanceolata* type, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and C:N plotted passively over principal component analysis (PCA) bi-plot for **a)** chironomid samples, highlighting changes in species composition through time and **b)** for common chironomid taxa. Legend: *Ablabesmyia* = ABLA, *Brillia* = BRLL, *Chaetocladius piger*-type = CHTp, *Chironomus anthracinus*-type = CHRa, *Chironomus plumosus*-type = CHRp, *Cladopelma* = CLAD, *Cladotanytarsus mancus*-type = CLTM, *Corynoneura arctica*-type = COar, *Corynoneura coronata*-type = COco, *Corynoneura edwardsi*-type = COed, *Corynoneura lobata*-type = COlo, *Corynoneura* type A = COta, *Corynoneura* undifferentiated = COud, *Cricotopus cylindraceus*-type = CRic, *Cricotopus intersectus*-type = CRli, *Cricotopus* type P = CRlp, *Dicrotendipes nervosus*-type = DICn, *Endochironomus albipennis*-type = ENDa, *Endochironomus tendens*-type = ENDt, *Eukiefferiella claripennis*-type = EUKc, *Eukiefferiella devonica*-type = EUKd, *Eukiefferiella fittkai*-type = EUKf, *Eukiefferiella* undifferentiated = EUKu, *Glyptotendipes pallens*-type = GLYp, *Glyptotendipes severini*-type = GLYs, *Guttipelopia* = GUTT, *Gymnometriocnemus/Bryophaenocladus* = GYMN, *Heleniella* = HELN, *Heterotanytarsus* = HETE, *Heterotrissocladus marcidus*-type = HETR, *Krenopelopia* = KRNP, *Krenosmittia* = KRNS, *Lauterborniella* = LAUT, *Limnophyes/Paralimnophyes* = LIMN, *Macropelopia* = MCPL, *Metriocnemus eurynotus*-type = METe, *Metriocnemus terrester*-type = METt, *Micropsectra insignilobus*-type = MCPi, *Micropsectra junci*-type = MCPj, *Micropsectra pallidula*-type = MCPp, *Micropsectra* undifferentiated = MCPu, *Microtendipes pedellus*-type = MICp, *Nanocladius branchicolus*-type = NAb, *Nanocladius rectinervis*-type = NAre, *Orthocladus* type S = ORTs, *Parachironomus varus*-type = PCHv, *Paracladius* = PCLD, *Parakiefferiella bathophila*-type = PRKb, *Parametriocnemus/Paraphaenocladus* = PRMC, *Paramerina* = PARM, *Paratanytarsus* = PARA, *Paratendipes nudisquama* = PTnu, *Phaenopsectra flavipes*-type = PHfl, *Phaenopsectra* type A = PHta, *Polypedilum nubeculosum*-type = PONu, *Polypedilum sordens*-type = POso, *Psectrocladius sordidellus*-type = PSCs, *Pseudosmittia* = PSDS, *Pseudorthocladus* = PSOC, *Procladius* = PROC, *Prodiamesa* = PROD, *Rheocricotopus effusus*-type = RHeu, *Rheocricotopus fuscipes*-type = RHfu, *Rheocricotopus* undifferentiated = RHud, *Sergentia coracina*-type = SERG, *Smittia* = SMIT, *Stempellina* = STMP, *Stempellinella/Zavrelia* = STPz, *Symposiocladius* = SYMP, *Synorthocladus* = SYNO, *Tanypus* = TYPS, *Tanytarsus chinyensis*-type = TAch, *Tanytarsus lactescens*-type = TAla, *Tanytarsus lugens*-type = TAlu, *Tanytarsus mendax*-type = TAme, *Tanytarsus pallidicornis*-type = TApa, *Tanytarsus* undifferentiated = TAUd, *Thienemannimyia* = THMY, *Thienemanniella clavicornis*-type = THNc, *Tvetenia bavarica*-type = Tbav.

Zone 3 = c. 3610 - 3140 BC (956.5 - 912.5 cm). The main change in the chironomid community is reflected in the disappearance of *Tanytarsus lugens*-type from the stratigraphy by c. 3510 BC (947 cm). *Chironomus anthracinus*-type and *Tanytarsus* undif. continue to dominate the chironomid stratigraphy. *Chironomus anthracinus*-type peaks on two occasions at c. 3550 BC (950 cm) and c. 3310 BC (928 cm) with a small peak also at c. 3280 BC (934 cm), while *Tanytarsus* undif. has a small peak (15%) at c. 3580 BC (953 cm). *Phaenopsectra flavipes*-type, *Micropsectra insignilobus*-type, *Paratanytarsus*, *Procladius*, *Corynoneura* undif., *Corynoneura lobata*-type, *Corynoneura* type A, *Limnophyes/Paralimnophyes*, *Parakiefferiella bathophila*-type and *Parametriocnemus/Paraphaenocladus* occur in higher abundance and frequency than in Zone 2. The change in the community composition is evident in a shift back to the left in the PCA Axis ($\lambda=0.113$) (Figure 4.3a).

Zone 4 = c. 3140 - 2480 BC (912.5 - 839.5 cm). This zone is dominated by *Microtendipes pedellus*-type, *Micropsectra insignilobus*-type, *Tanytarsus* undif. and *Tanytarsus mendax*-type, while *Chironomus anthracinus*-type is less abundant than in previous zones. *Corynoneura* undif. and *Corynoneura lobata*-type are present at low abundance. Total stream taxa become more important in the stratigraphy. The change in the community composition is reflected in the PCA samples bi-plot, with samples from Zone 4 clustering to the left of the axis (Figure 4.3a). Division into two subzones acknowledges notable changes in the abundance of several chironomid types in this zone.

Sub-Zone 4a = c. 3140 - 2720 BC (912.5 - 867.5 cm). *Corynoneura* type A, *Limnophyes/Paralimnophyes* and *Parametriocnemus/Paraphaenocladus* are prominent in this sub-zone. *Chironomus anthracinus*-type is absent from c. 2950 - 2940 BC (894 - 893 cm) but re-enters the stratigraphy from c. 2930 - 2910 BC (892 - 890 cm) at 5%, in concert with small increases in abundance of *Micropsectra insignilobus*-type and *Tanytarsus* undif. *Chironomus anthracinus*-type is absent once again at c. 2900 BC (889 cm). *Orthocladus* type S, *Endochironomus albipennis*-type, *Glyptotendipes pallens*-type and *Nanocladus branchicolus*-type become more frequent in the chironomid stratigraphy in the upper half of this sub-zone. *Symposiocladius*, a wood miner in running water, is also present.

Sub-Zone 4b = c. 2720 - 2480 BC (867.5 - 839.5 cm). *Chironomus anthracinus*-type remains at an average of 5% in sub-Zone 4b, with an increase in abundance to 8% between c. 2530 - 2510 BC (845 - 843 cm). *Chironomus plumosus*-type enters the stratigraphy with an average of 5% between 2530 - 2510 BC (845 - 843 cm). Notably high abundances of *Tanytarsus* undif., *Paratanytarsus*, *Micropsectra insignilobus*-type and *Microtendipes pedellus*-type are recorded. *Endochironomus albipennis*-type,

Glyptotendipes pallens-type and *Nanocladius branchicolus*-type remain low in abundance in continuation from sub-Zone 4a. *Cladopelma*, *Cricotopus intersectus*-type and the terrestrial taxon *Smittia* become more frequent than in sub-Zone 4b. *Symposiocladius* is also present. Total stream taxa average at 17% between 2680 - 2630 BC (862 - 857 cm).

4.5.2 Stable carbon and nitrogen isotopes and loss on ignition

Values of lake sediment $\delta^{15}\text{N}$ range from 2.3 - 5.4‰ with a mean of 3.9‰ and total nitrogen (TN) shows a range of 0.9 - 1.7% (mean = 1.3%; Figure 4). The values for $\delta^{13}\text{C}$ vary from -30.5 to -32.6‰, with a mean of -31.6‰. C:N ratios of organic matter show a range of 11.3 - 14.6, with a mean value of 13.3. LOI_{550} values range from 19.8 - 43.7% (mean = 32.7%) and NCF values vary from 44.9 - 61.7% (mean = 51.5%). The zones established for the chironomid data were also applied to the other proxies to allow for an easier comparison of the various datasets.

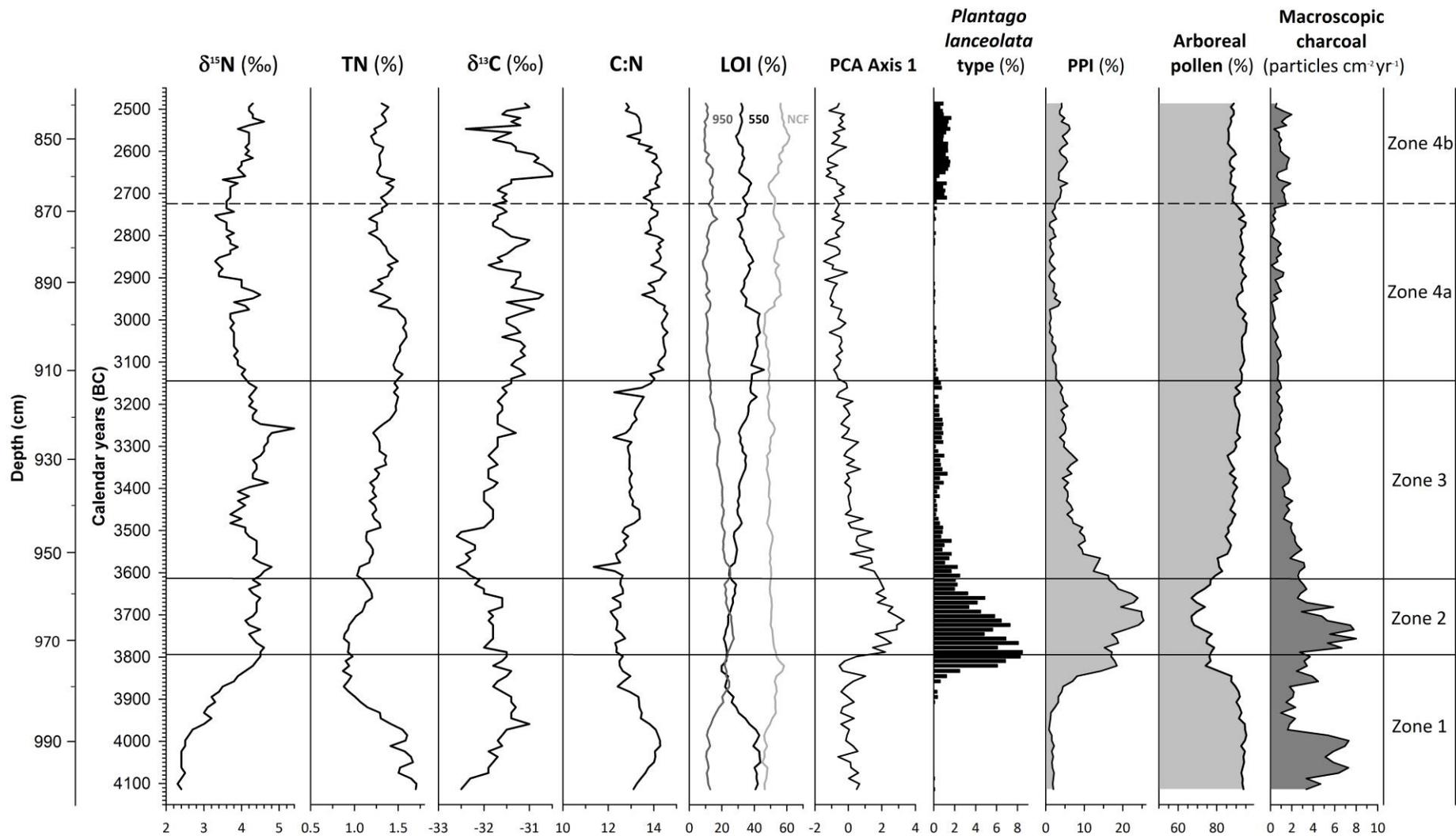


Figure 4.4 - A comparison of geochemical data, LOI (550 °C, 950 °C and NCF), chironomid PCA Axis 1 values, pastoral pollen indicators (PPI), *Plantago lanceolata* type, total arboreal pollen and macroscopic charcoal for Templevanny Lough, Co. Sligo.

Zone 1 = c. 4120 - 3790 BC (999.5 - 973.5 cm). Levels of $\delta^{15}\text{N}$ show a gradual increase from 2.3 - 4.5‰ through Zone 1 (Figure 4.4). $\delta^{13}\text{C}$ values increase from -32.5 to -31‰ by 3960 BC (987 cm) and decrease afterwards to -31.5‰. An increase of the C:N ratio from 13.0 - 14.3 is recorded between c. 4110 - 4010 BC (999 - 991 cm), after which it decreases to 12.4.

Zone 2 = c. 3790 - 3610 BC (973.5 - 956.5 cm). Elevated $\delta^{15}\text{N}$ levels of 4.1 - 4.6‰ are recorded, while $\delta^{13}\text{C}$ decreases from -31.5 to -32.2‰ and C:N remains consistently low at 12 through this zone.

Zone 3 = c. 3610 - 3140 BC (956.5 - 912.5 cm). $\delta^{15}\text{N}$ ranges from 5.4 - 3.7‰. There are three peaks in $\delta^{15}\text{N}$ at c. 3590 BC (954 cm; 4.8‰), c. 3390 BC (935 cm; 4.7‰) and c. 3260 BC (923 cm; 5.4‰), and a notable low of 3.8‰ is observed from c. 3480 - 3460 BC (944 - 942 cm). The C:N ratio show an increasing trend.

Sub-Zone 4a = c. 3140 - 2720 BC (912.5 - 867.5 cm). $\delta^{15}\text{N}$ is represented by generally lower values than in Zone 3. A peak of 4.2‰ is observed from c. 2980 - 2910 BC (897 - 890 cm), with an average of 3.7‰ through the remaining samples in this zone. $\delta^{13}\text{C}$ shows higher levels than in Zone 3, with an average value of -31.4‰ and a peak of -30.8‰ at c. 2950 BC (894 cm). The C:N ratio show a notable trough from c. 2980 - 2910 BC (897 - 890 cm), with values reaching 13.5 at c. 2940 (893 cm). Excluding this period, C:N values average at 14.2. LOI_{550} shows a notable trough from c. 2980 - 2880 BC (897 - 886 cm) reaching a low of 32% at c. 2930 BC (892 cm).

Sub-Zone 4b = c. 2720 - 2480 BC (867.5 - 839.5 cm). $\delta^{15}\text{N}$ values steadily increase throughout this sub-zone. $\delta^{13}\text{C}$ values fluctuates substantially, with a large increase to -30.7‰ between c. 2660 - 2610 BC (860 - 854 cm). C:N values decline from c. 2600 BC (847 cm). LOI_{550} shows a declining trend, with a decrease of 8% documented between c. 2680 - 2650 BC (862 - 859 cm). NCF values increase from 49 - 61% between c. 2680 - 2570 BC (863 - 850 cm).

4.5.3 Pollen and macroscopic charcoal

Macroscopic charcoal accumulation rates range from 0.1 - 8 particles $\text{cm}^{-2}\text{yr}^{-1}$, with a mean value of 1.9 particles $\text{cm}^{-2}\text{yr}^{-1}$ (Figure 4.4).

Zone 1 = c. 4120 - 3790 BC (999.5 - 973.5 cm). High levels of macroscopic charcoal of 3 - 6 particles $\text{cm}^{-2}\text{yr}^{-1}$ are found at the beginning of the stratigraphy from c. 4110 - 4000 BC (999 - 990 cm), with peaks at c. 4060 BC (995 cm; 7.3 particles $\text{cm}^{-2}\text{yr}^{-1}$) and at c. 4000 BC (990 cm; 7.3 particles $\text{cm}^{-2}\text{yr}^{-1}$).

Despite lower levels thereafter another peak of 4.5 particles $\text{cm}^{-2}\text{yr}^{-1}$ is recorded at c. 3860 BC (979 cm). Following low values of <1%, PPI values rise moderately from 1 - 8% between c. 3970 - 3850 BC (988 - 978 cm), followed by a steeper rise to 19% by c. 3820 BC (976 cm). Initially, Poaceae: wild grass group pollen contributes largely to this increase (cf. Stolze et al., 2013b). The *P. lanceolata* type pollen curve begins to rise at 3850 BC (980 cm). The rise in PPI is accompanied by a decline in arboreal pollen from 95 to 88% between c. 3970 - 3850 BC (988 - 978 cm), falling to 76% by c. 3820 BC (976 cm).

Zone 2 = c. 3790 - 3610 BC (973.5 - 956.5 cm). PPI, dominated by Poaceae: wild grass group and *P. lanceolata* type pollen, attain their highest abundance of 25% within the stratigraphy c. 3730 - 3690 BC (968 - 964 cm).

Zone 3 = c. 3610 - 3140 BC (956.5 - 912.5 cm). Levels of macroscopic charcoal and PPI decrease from 3 - 0.5 particles $\text{cm}^{-2}\text{yr}^{-1}$ and from 16 - 4 %, respectively. Despite this trend, PPI, *P. lanceolata* type and macroscopic charcoal show peaks at c. 3600 - 3560 BC (955 - 951 cm) and c. 3390 - 3300 BC (935 - 927 cm).

Sub-Zone 4a = c. 3140 - 2720 BC (912.5 - 867.5 cm). Macroscopic charcoal levels are very low at 0.1 - 1.4 particles $\text{cm}^{-2}\text{yr}^{-1}$. PPI percentages are also low at c. 2%, with the exception of a slight peak of c. 3% between c. 2970 - 2940 BC (896 - 893 cm). *P. lanceolata* type appears in trace amounts between c. 2960 - 2910 BC (895 - 890 cm). Arboreal pollen is present between 90-95%.

Sub-Zone 4b = c. 2720 - 2480 BC (867.5 - 839.5 cm). Values of macroscopic charcoal are higher than in the previous zone. Levels of PPI increase to c. 4%, and peak at 6% at c. 2550 BC (847 cm). Poaceae: wild grass group and *P. lanceolata* type pollen are the main contributors to PPI.

4.5.4 Redundancy Analysis (RDA)

RDA produced eigenvalues for Axis 1 of $\lambda=0.093$ and for Axis 2 of $\lambda=0.040$. Analysis identified that the six chosen environmental variables (PPI, *P. lanceolata* type, macroscopic charcoal, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and C:N) have statistically significant ($p < 0.01$) relationships with the chironomid composition (Figure 4.5; Table 4.1).

Partial RDAs show that PPI exhibited the strongest correlation with the chironomid community, explaining 8.4% of the variance on its own and 2.5% with other variables partialled out (Table 4.1). A linear regression further highlights a strong relationship between PCA Axis 1 and the

PPI data ($r^2 = 0.689$, $p < 0.01$; Table 4.1). Macroscopic charcoal (6.2% variance), *P. lanceolata* type (6.1% variance) and C:N (6.0% variance) also exhibited strong relationships with the chironomid assemblage data (Table 4.1).

The RDA bi-plot highlights that PPI and *P. lanceolata* type are likely the main variables behind the chironomid community change in Zone 2 (Figure 4.5). C:N and $\delta^{13}\text{C}$ show a relationship with the chironomid assemblage of Zone 4, with higher values in the environmental variables corresponding with Zone 4 samples in the bi-plot. RDA analysis also shows that the chironomid community in Zone 1 correspond with the low $\delta^{15}\text{N}$ values.

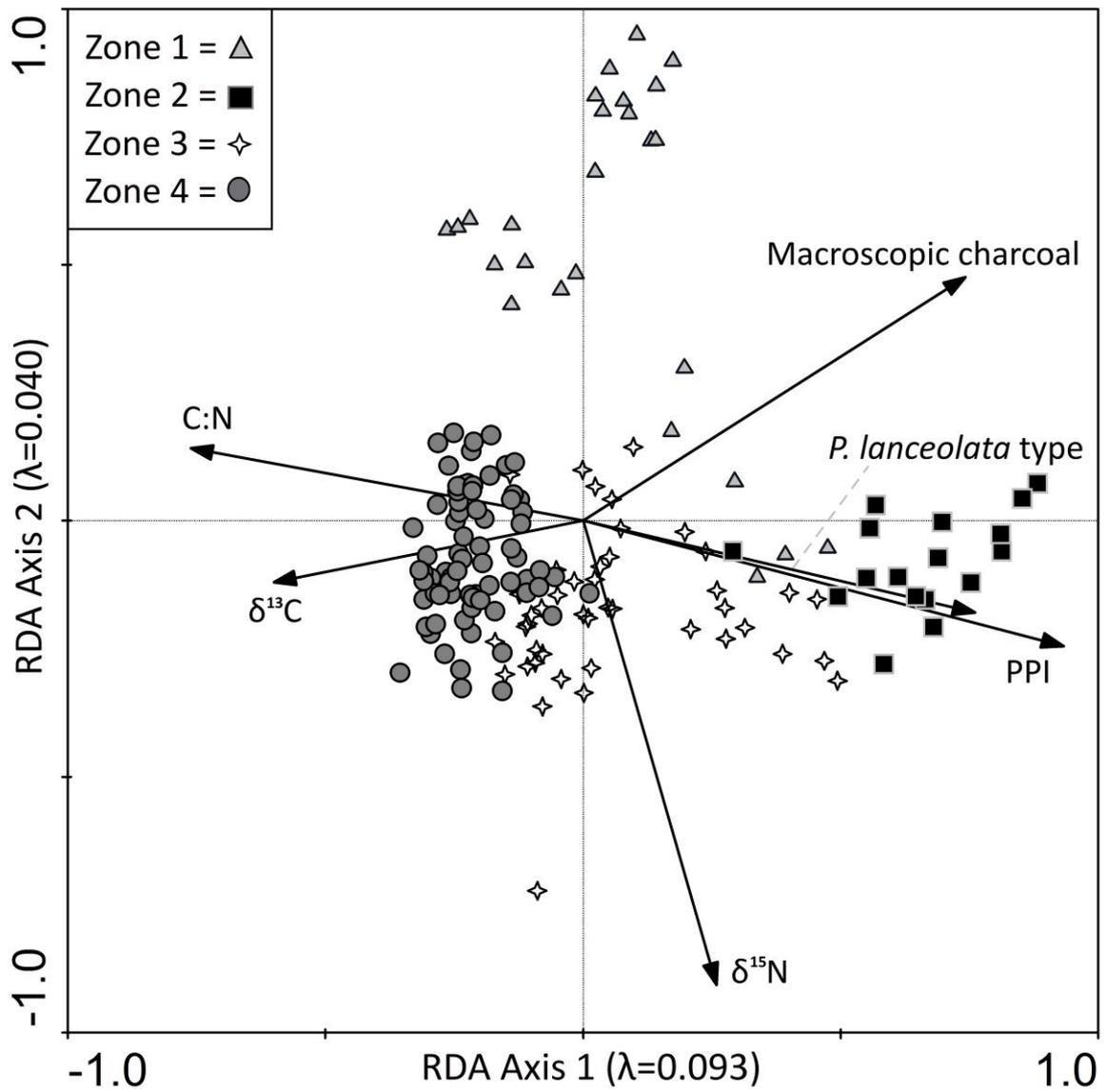


Figure 4.5 - Redundancy analysis (RDA) biplot for chironomid samples with environmental variables - macroscopic charcoal, pastoral pollen indicators (PPI), *Plantago lanceolata* type, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and C:N.

Table 4.1 - Partial redundancy analyses (RDA) for environmental variables by themselves and with the effects of other environmental variables partialled out. Table also includes for each variable a linear regression correlation co-efficient with chironomid PCA Axis 1.

Variable	Covariables	λ_1	λ_1/λ_2	P	% variance	PCA Axis 1 as predictor (R^2)
PPI	None	0.084	1.292	0.002	8.4	0.689 *
	Charcoal, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N	0.021	0.447	0.002	2.5	
<i>Plantago lanceolata</i> type	None	0.061	0.801	0.002	6.1	0.444 *
	Charcoal, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N	0.014	0.298	0.002	1.7	
$\delta^{15}\text{N}$	None	0.041	0.373	0.002	4.1	0.054 *
	Charcoal, <i>P. lanceolata</i> type, PPI, $\delta^{13}\text{C}$, C:N	0.022	0.468	0.002	2.6	
$\delta^{13}\text{C}$	None	0.043	0.518	0.002	4.3	0.312 *
	Charcoal, <i>P. lanceolata</i> type, PPI, $\delta^{15}\text{N}$, C:N	0.013	0.277	0.002	1.5	
C:N	None	0.060	0.870	0.002	6.0	0.470 *
	Charcoal, <i>P. lanceolata</i> type, PPI, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$	0.015	0.319	0.002	1.8	
Macroscopic charcoal	None	0.062	0.775	0.002	6.2	0.434 *
	<i>P. lanceolata</i> type, PPI, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N	0.011	0.234	0.002	1.3	

PPI: pastoral pollen indicator; PCA: principal component analysis.* p value of < 0.01

4.6 Discussion

Based on the chironomid record four phases of lake productivity and land-use change at Templevanny Lough during the Irish Neolithic were discerned. Comparison with pollen and macroscopic charcoal as proxies of terrestrial land-use change provides evidence that anthropogenic activity within the lake catchment had a measurable impact on the lake system through nutrient loading and subsequent lake eutrophication during the Neolithic.

4.6.1 Zone 1 – Early anthropogenic disturbance and onset of Neolithic farming

High levels of macroscopic charcoal recorded from c. 4110 - 4000 BC, indicate local natural or anthropogenic fire activity (Whitlock and Larsen, 2001), pre-dating widespread forest clearance in the region (cf. O'Connell et al., 2014; Stolze et al., 2013b). Microscopic and macroscopic charcoal were also present around this time at Cooney Lough (O'Connell et al., 2014) and Lough Dargan (Taylor et al., 2013), both located within a c. 20 km radius of the study site. The timing of this peak in macroscopic charcoal also coincides with the construction dates for the early causewayed enclosure at Magheraboy, Co. Sligo (Danaher, 2007). Together with the presence of *Pteridium aquilinum* spores (Stolze et al., 2013b) and occasional *P. lanceolata* type pollen, the record points to human related disturbances. Chironomids do not exhibit a noticeable response to this early activity, as it was likely not at a scale that would influence lake trophic status. However, high C:N ratios and increasing $\delta^{13}\text{C}$ values infer greater terrestrial inputs during this time.

An initial decrease in the forest cover occurs between c. 3970 and 3850 BC and coincides with the mid-Holocene elm decline (Stolze et al., 2013b). The gradual increase in $\delta^{15}\text{N}$, NCF and decrease in C:N suggest nutrient influx and enhanced productivity of Templevanny Lough as a result of soil destabilization due to loss of canopy (cf. Cohen, 2003). The chironomid community shows a subdued response to this vegetational change. *Cladopelma*, which is not particularly tolerant of high nutrient conditions (Brooks et al., 2007; Moller Pillot, 2009), disappears by c. 3930 BC, only to return sporadically in low numbers for the remainder of the Neolithic period.

Increased fire activity at c. 3860 BC, as evident in the macroscopic charcoal record precede the accelerated deforestation at c. 3850 BC. The pronounced increase in PPI, in particular *P. lanceolata* type pollen, from c. 3850 - 3820 BC indicates the onset of Neolithic pastoral farming activity in the catchment area of Templevanny Lough. The chironomid community composition shows a markedly stronger response to pastoral farming activity than to the previous loss in forest cover linked to the elm decline. However, the chironomids seem to experience a lagged response to the anthropogenic activity. The lagged effect occurs throughout the sampling range by one to two

samples (~10 - 20 years). For example, the resulting impact of an increase in PPI from 3850 - 3820 BC is seen two samples later by an increase in *Tanytarsus mendax*-type from 5 - 17% and *T. lugens*-type from 0 - 6% from c. 3810 - 3800 BC. *Tanytarsus mendax*-type, a warm stenotherm has previously been associated with pastoral agriculture in western Ireland (Potito et al., 2014; Taylor et al., 2013). *Tanytarsus lugens*-type however, is usually associated with oligotrophic lakes (Brooks et al., 2007; Saether, 1979) but appears to be responding to the increased nutrient input at Templevanny Lough. This taxon also shows an association with warm, productive lakes in western Ireland surface sediments (Potito et al., 2014). Wilson and Gajewski (2004) noted that *T. lugens*-type was common in shallow, productive lakes in Northern British Columbia and suggest the possibility that *T. lugens*-type has a more widespread ecological distribution than previously thought. Cool summer conditions in Ireland (~16°C July temperature average; Met Éireann, 2016) may result in *T. lugens*-type exhibiting a similar ecological response to nutrient enrichment, as *T. lugens*-type in colder regions. However, this taxon has been associated with cold late-glacial conditions in a small lake in County Donegal, Ireland (Watson et al., 2010), suggesting that the full ecological distribution of *T. lugens*-type in Ireland may merit further investigation. Lag effects between land-use change and lake eutrophication could be due to within-lake nutrient cycling or delayed nutrient inwash (Genkai-Kato and Carpenter, 2005). Response times can be highly variable and are affected by catchment morphology and soil type, lake morphometry, temperature and dominance of macrophytes, among other factors (Genkai-Kato and Carpenter, 2005). In the short term, accumulation of nitrogen and phosphorus in the soils from manure is an important driver of nutrient input. Nutrient-rich soils are washed into lakes, where some of the phosphorus dissolves and stimulates growth of phytoplankton and aquatic plants (Carpenter, 2005). Within-lake recycling of nutrients from sediments and consumers can then act to enhance eutrophication through time (Carpenter et al., 1998; Carpenter, 2005). Templevanny Lough geochemistry does not show a lag with land-use change, so within-lake nutrient cycling, rather than delayed nutrient in-wash, is likely responsible for the lagged chironomid response.

Chironomid larvae do not exploit nutrients directly, but instead indirectly respond to changes in the availability of food (mainly diatoms, organic detritus and macro-invertebrates) and benthic oxygen conditions (Brooks et al., 2001). Chironomids can exhibit a gradual or threshold response to nutrient inputs, and response time to cultural eutrophication can often lag land-use change (Langdon et al., 2006). Lotter and Birks (2003) note a lag of several centuries in the chironomid community in response to changes within an aquatic ecosystem of a small lake, Sägistalsee in the Swiss Alps. A lagged chironomid response was not visible in the Lough Dargan record, presumably as a result of the low sampling resolution of 35 to 270 years (mean = 70 years)

(Taylor et al., 2013). Interestingly, lagging Templevanny Lough PPI and *P. lanceolata* type pollen by 2 samples (~20 years) results in marginally more powerful partial RDAs (8.5% explained variance for PPI; 7.5% explained variance for *P. lanceolata* type) and stronger relationships with chironomid PCA Axis 1 ($r^2 = 0.713$ for PPI; $r^2 = 0.586$ for *P. lanceolata* type) than the non-lagged models used in this paper.

4.6.2 Zone 2 – Early Neolithic farming

The most intensive period of Neolithic farming activity at Templevanny Lough coincides with high levels of archaeological activity found in Ireland between c. 3750 - 3500 BC, including the construction of rectangular houses between 3715 - 3625 BC (Whitehouse et al., 2014). The causewayed enclosure at Magheraboy and the Carrowmore passage tomb complex provide evidence of human activity in the Sligo area during the early Neolithic (Bergh, 1995; Danaher, 2007; Hensey and Bergh, 2013). Neolithic farming at Templevanny Lough precedes dates from Carrowkeel-Keshcorran cairns by several centuries, although the Carrowkeel-Keshcorran dates may be compromised by insecure stratigraphic contexts (Hensey, 2015).

High levels of PPI and *P. lanceolata* type indicate sustained open pasture between c. 3730 - 3690 BC (Figure 4.4). High $\delta^{15}\text{N}$ values (4.1 - 4.6‰), together with the decrease in $\delta^{13}\text{C}$ and low C:N suggest considerable nutrient enrichment in the lake system. High $\delta^{15}\text{N}$ values in concert with decreasing levels of TN and $\delta^{13}\text{C}$ are often indicative of pastoral farming around a lakeside and the inwash of animal waste into a lake (Botrel et al., 2014; Taylor et al., 2013; Woodward et al., 2012). A similar geochemical pattern of increased $\delta^{15}\text{N}$, low $\delta^{13}\text{C}$ concomitant with high farming activity was recorded at Lough Dargan, supports the assumption of animal husbandry with substantial levels of animal waste reaching the lake during the Neolithic (Taylor et al., 2013). Furthermore, $\delta^{13}\text{C}$ in modern lake sediment samples from agricultural catchments in western Ireland were more negative in value than $\delta^{13}\text{C}$ in samples from non-impacted sites (Woodward et al., 2012). Averaged $\delta^{15}\text{N}$ (4.4‰), $\delta^{13}\text{C}$ (-31.8‰) and C:N (12.4) values place the early Neolithic at Templevanny Lough among lakes with >80% agricultural cover (mostly pastoral) within a 50-lake training set of modern lakes in western Ireland (Woodward et al., 2012).

The chironomid community in Zone 2 shows eutrophic taxa such as *Chironomus anthracinus*-type, *Tanytarsus* undif. and *Tanytarsus lugens*-type dominating the stratigraphy (Figure 4.2). *T. lugens*-type is associated with modern agricultural activity in a western Ireland training set (Potito et al., 2014). *T. lugens*-type appears to have taken advantage of the new ecological opportunities following the onset of early Neolithic farming, and rapidly dominates the chironomid stratigraphy. A decrease in *T. lugens*-type towards the end to this phase suggests that *T. lugens*-type may have been

at a competitive disadvantage, eventually becoming replaced by other eutrophic taxa, mainly *Chironomus anthracinus*-type, an opportunistic eutrophic taxon linked to agriculture in western Ireland (Potito et al., 2014). The apparent decrease in *Corynoneura lobata*-type and *Corynoneura* type A appear to follow well with the decline in total stream taxa during Zone 2. *Corynoneura* as a genus can be found in a variety of different water bodies such as lakes, pools, streams, springs and marshes, with *Corynoneura lobata*-type in particular, being an inhabitant of running water (Moller Pillot, 2013).

4.6.3 Zone 3 – Decline in farming activity

Farming activity in the Templevanny Lough catchment wanes during the middle Neolithic, with periods of small scale activity. Lower $\delta^{15}\text{N}$ values in Zone 3 correspond with reduced farming activity as reflected in the PPI (Figure 4.4). Increasing C:N shows decreased lake productivity through time. This is in keeping with a lull in human activity, with settlement evidence appearing more ephemeral in Ireland between c. 3400 - 3000 BC (Whitehouse et al., 2014). Although farming was declining at Templevanny Lough, human impact on the lake system persisted, with *Chironomus anthracinus*-type and *Tanytarsus* undif. remaining dominant during this time. This is expected, as lakes are known to take decades to centuries to recover from cultural eutrophication (Carpenter, 2005).

The PPI, *P. lanceolata* type pollen, $\delta^{15}\text{N}$ and macroscopic charcoal data indicate two main intervals of human activity in the area during the middle Neolithic at c. 3600 - 3560 BC and c. 3390 - 3300 BC. Small fluctuations in the abundances of *Tanytarsus* undif. and *Chironomus anthracinus*-type suggest increased nutrient input as a result of this small scale farming activity. This evidence shows that although farming activity is reduced, humans remain an active part of the landscape during this time.

Based on the proxy data, Templevanny Lough remains productive during the middle Neolithic likely due to sustained farming and/or prolonged lake recovery from earlier farming activity. The main chironomid taxa present during this time including *Chironomus anthracinus*-type, *Micropsectra insignilobus*-type, *Tanytarsus mendax*-type, *Tanytarsus* undif., *Paratanytarsus*, *Corynoneura* undif., *Corynoneura* type A, *Limnophyes/Paralimnophyes* and *Phaenopsectra flavipes*-type, indicate a macrophyte-rich, eutrophic lake. Floating leaf macrophytes occurred in the lake throughout this period (Stolze et al., 2013b).

Micropsectra insignilobus-type appears anomalously in this stratigraphy as it is a cold stenotherm associated with oligotrophic lakes (Brooks et al., 2007). However, *M. insignilobus*-type subfossils are indistinguishable from *M. atrofasciata*-type (Brooks et al., 2007), which occurs in eutrophic rivers and increase below sewage discharges (Brooks et al., 2007; Wilson, 1989). Ruiz et al.

(2006) also noted increases in *M. insignilobus*-type with nutrient enrichment in an investigation of a palaeochannel in the East Midlands, UK and altered the identification of the *M. insignilobus*-type to *M. atrofasciata*-type based on its ecology.

4.6.4 Sub-Zone 4a – Low farming activity during the late Neolithic

The palynological data and $\delta^{15}\text{N}$ indicate low levels of farming activity and woodland recovery during most of the late Neolithic, with the exception of an increase in activity around c. 2980 - 2910 BC (Figure 4.4). A significant decrease in the abundance of the eutrophic taxon *Chironomus anthracinus*-type clearly reflects this downturn. Averaged $\delta^{15}\text{N}$ (3.7‰), $\delta^{13}\text{C}$ (-31.4‰) and C:N (14.2) values place this sub-zone, excluding the increase in values between c. 2980 - 2910 BC, among lakes with 20 - 80% agricultural cover within the 50-lake training set of modern lakes in western Ireland (Woodward et al., 2012). The chironomid community is largely dominated by taxa associated with macrophytes and/or terrestrial/semi-terrestrial habitat, including *Microtendipes pedellus*-type, *Limnophyes/Paralimnophyes*, *Corynoneura* undif., *Corynoneura* type A and *Symposiocladius* (cf. Stolze et al., 2013b).

The $\delta^{15}\text{N}$, *P. lanceolata* type pollen and PPI data indicate a short-lived period of small-scale pastoral farming for 70 years between c. 2980 - 2910 BC, peaking at c. 2940 BC. Despite the ephemerality of this interval, the impact on the lake system is evident particularly in the geochemical data with fluctuations in $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N and LOI_{550} . C:N ratios infer increased lake productivity during this time, $\delta^{15}\text{N}$ is elevated and LOI_{550} decreases by 7%, possibly indicating inwash of allochthonous material (cf. Stolze et al., 2013b). The chironomid response to this period of small scale farming activity is more subtle, with slight increases in *Chironomus anthracinus*-type, *Tanytarsus* undif. and *Micropsectra insignilobus*-type during this time. This period of farming coincides with an interval of possible activity at the Carrowkeel-Keshcorran complex from approximately c. 3200 - 2900 BC, as evidenced by human bone remains and dated charcoal (Hensey et al., 2013). This period (3200 - 2900 BC) also represents a critical time in the passage tomb construction and use in the eastern part of Ireland (Hensey et al., 2013).

4.6.5 Sub-Zone 4b – Return of farming at the end of the Neolithic period

Increases in $\delta^{15}\text{N}$, PPI and macroscopic charcoal signify a return of small-scale farming activity around Templevanny Lough. Sub-Zone 4b marks the possible build up to the early Bronze Age farming in the Carrowkeel-Keshcorran area (cf. Hensey et al., 2013). The C:N ratio decreases at Templevanny Lough, suggesting an increase in autochthonous productivity from c. 2600 BC. A

decrease in LOI_{550} and increase in NCF values suggest influx of allochthonous material, possibly leading to nutrient enrichment of the lake system.

The $\delta^{13}C$ values fluctuate substantially during the later Neolithic. The elevated values between c. 2660 - 2610 BC could be indicative of a possible inwash event, changes in lake level or an increase in macrophyte productivity. Increased C:N ratios during this time provide evidence of terrestrial material being deposited into the lake, which is supported by high NCF. $\delta^{15}N$, TN and the presence of *P. lanceolata* type pollen and macroscopic charcoal suggest that this increase in $\delta^{13}C$ is not directly land-use related. Chironomid taxa associated with terrestrial material, including *Limnophyes/Paralimnophyes*, *Smittia* and *Symposiocladius*, are present during this time. Furthermore, the increase in total stream taxa and $\delta^{13}C$ values, likely indicate increased inflow from the surrounding streams.

The chironomid community indicates a eutrophic, macrophyte-rich lake with the presence of *Chironomus anthracinus*-type, *Chironomus plumosus*-type, *Tanytarsus* undif., *Paratanytarsus*, *Endochironomus albipennis*-type, *Glyptotendipes pallens*-type and *Cricotopus intersectus*-type in various lagged responses to the farming activity. The emergence of *Chironomus plumosus*-type and an increase in $\delta^{15}N$ from c. 2530 BC coincides in an increase in PPI at c. 2550 BC, signifying substantial nutrient input to the lake system. *Chironomus plumosus*-type is a eutrophic taxon that has been used as an indicator of hypertrophic conditions in Danish lakes (Brodersen and Lindegaard, 1999).

4.6.6 Palaeolimnological impacts of Neolithic farming

The timing and magnitude of changes in the chironomid stratigraphy show that land-use, potentially influenced by climate change (Stolze et al. 2013b), is the main control on the chironomid community at Templevanny Lough during the Neolithic. Although chironomids have been mostly used as a palaeotemperature indicator in the past, as temperature tends to be the main driver behind chironomid community compositional change (Brooks and Birks, 2001), more recent studies have shown that even moderate human impacts are sufficient enough to over-ride the climate signal in the chironomid record (Brodersen and Quinlan, 2006; McKeown and Potito, 2016), which seems to be the case in Templevanny Lough.

RDA and partial RDAs show a strong statistical relationship between PPI and *P. lanceolata* type pollen with the changes in the chironomid composition, with the relationship especially apparent for Zone 2 (Figure 4.5). The strong correlation between PCA Axis 1 and PPI further highlights that pastoral land-use was a dominant influence on chironomid community compositional change throughout the record. Additionally, the chironomid community as reflected in the PCA Axis

and the main chironomid taxa (e.g. *T. lugens*-type) show the same structural coherence as the PPI data in a lagged response (Figure 4.4). The chironomid community composition thus exhibited a predictable and proportional lagged response of c. 10 - 20 years after the farming activity occurred. If the chironomid community was directly driven by climatic forcing, the composition would change before or at the same time as any increase or decrease in human activity occurred in the catchment area because farming around Templevanny Lough during the Irish Neolithic was shown to follow climatic variation closely (Stolze et al., 2013b).

Organic residue analysis from pottery shows cattle dairying to be especially prominent in this area during the Neolithic (cf. Smyth and Evershed, 2015), so it is likely that lake trophic status is tied to pastoral activity of cows during this time. As the palaeolimnological proxies show a scaled response, rather than a simple threshold response, to Neolithic land-use change (Langdon et al., 2006), they can be used as reliable proxies for prehistoric land-use intensity. However, the chironomid response was systematically lagged throughout the record, likely due to within-lake nutrient dynamics (cf. Carpenter, 2005). Therefore, palynological evidence should be used to represent and date the onset and timing of Neolithic farming, whereas palaeolimnological evidence can show the intensity and environmental impacts of these activities.

Early Neolithic farming resulted in environmental impacts and freshwater eutrophication that would put Templevanny Lough on a par with lakes from modern pastoral catchments in the region (Woodward et al., 2012). The considerable impacts could be due to scale of activity (i.e. sizeable cattle herds) or location of grazing activity (i.e. adjacent to the lakeside). Either way, evidence from Templevanny Lough and Lough Dargan (Taylor et al., 2013), both in fertile lowland areas, shows that prehistoric pastoral farming practices regularly result in lake eutrophication across the region.

4.7 Conclusions

This paper provides the first reconstruction of a lake's trophic state in response to anthropogenic activity at a decadal resolution of the Irish Neolithic. The large volume of data enabled a detailed reconstruction of the chain of events associated with the onset of farming activity in the catchment area as well as providing information on the timing, intensity and environmental impact of anthropogenic activity. The chironomid community responded to farming activity in a lagged response of c. 10 - 20 years throughout the study period, and this is the first chironomid study to show such a systematic lagged response throughout a prehistoric record. This timeline of events can now be used to inform and enhance the archaeological database for the Carrowkeel-Keshcorran

megalithic complex, including grazing location, timing and magnitude of land-use change within the Templevanny Lough catchment and environmental impacts of pastoral farming in the region.

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Chapter 5 - Paper Two

“Impact of early prehistoric farming on chironomid communities in northwest Ireland”

Impact of early prehistoric farming on chironomid communities in northwest Ireland

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Keywords

Chironomids, Neolithic, Bronze Age, Prehistoric farming, Eutrophication, Stable isotopes, Ireland.

5.1 Abstract

This study explored the utility and performance of chironomid (Diptera: Chironomidae) autecology in the investigation of prehistoric farming impacts on freshwater lake systems. Chironomid subfossils, lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N), pollen and macroscopic charcoal analyses were used in a comparative limnological assessment of three archaeologically rich study sites in northwest Ireland. At all three study sites, pastoral farming and its associated nutrient inputs, as represented by non-arboreal pollen indicative of grassland/pasture (NAPP) and lake sediment geochemistry, are concomitant with increases in eutrophic chironomid taxa. Redundancy analysis (RDA) and partial RDAs established that $\delta^{15}\text{N}$ and NAPP were controlling factors of chironomid community compositional change during the Neolithic (4000-2500 BC) and Bronze Age (2500-600 BC). Bronze Age farming had a considerably greater impact on the lake systems than Neolithic farming, as indicated by a higher proportion of eutrophic taxa and increases in $\delta^{15}\text{N}$, C:N and $\delta^{13}\text{C}$ values, consistent with increased erosion and agricultural inputs. Findings emphasise the importance of identifying the natural, pre-impacted state of a lake system to determine the extent of agricultural impact accurately. The timing and magnitude of change show that Neolithic and Bronze Age farming exhibited a strong control over chironomid communities at all three sites.

5.2 Introduction

Chironomid (Diptera: Chironomidae) subfossils in lake sediment cores are an excellent biological method for reconstructing past limnological conditions, as chironomid larvae are extremely sensitive to changes within freshwater lake systems (Walker 2001). Although chironomids are commonly used as palaeotemperature indicators, chironomid communities are affected by a variety of environmental variables including lake nutrient status (Eggermont and Heiri 2012). Recent studies highlight the potential for species-specific chironomid autecology in environmental and archaeological contexts (Ruiz et al. 2006; Ruess et al. 2013). Additionally, stable isotopic analysis of carbon and nitrogen ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) and C:N ratios offer invaluable insights into past lake conditions by providing information on nutrient loading, lake productivity, sources of lake-sediment organic matter and changing land use practices (Cohen 2003; Woodward et al. 2012). Both chironomid and geochemical analyses are fully established methods of inquiry in the field of palaeolimnological research. Few studies, however, utilise these indicators to their full potential by comparing biotic and geochemical indicators in a palaeoenvironmental context. Exceptions include Itkonen et al. (1999), Axford et al. (2009) and Medeiros et al. (2014). Two recent studies (Taylor et al. 2013, 2016) employed the autecology of chironomid subfossils in a comparative approach with geochemical, pollen and macroscopic charcoal analysis at two archaeologically rich study sites to establish linkages between early prehistoric land use and lake eutrophication in Ireland.

Nutrient loading associated with agriculture indirectly impacts chironomid communities through changes in the availability of food (mainly diatoms, organic detritus and macro-invertebrates) and reduced benthic oxygen levels (Brooks et al. 2001). Chironomids have been shown to exhibit a gradual or threshold response to nutrient inputs (Lotter and Birks 2003; Taylor et al. 2016). In pastoral areas, phosphorus and nitrogen from manure accumulate in the surrounding catchment soils and can be an important driver of nutrient input. Nutrient-rich soils are deposited into the lake system, where some of the phosphorus dissolves and stimulates growth of macrophytes and phytoplankton. Within-lake recycling of nutrients from sediments and consumers can then act to enhance eutrophication through time (Carpenter et al. 1998; Carpenter 2005).

The Neolithic (4000-2500 BC) and Bronze Age (2500-600 BC) are well-constrained time periods in Irish prehistory (Waddell 2010) that can be used to test the potential of chironomids as ecological indicators of lake response to early farming activity. Northwest Ireland had a prominent Neolithic and Bronze Age, with County Sligo in particular having one of the highest concentrations of megalithic tombs in Ireland (Bergh 1995). The Neolithic saw the first major human impact on the landscape with the introduction of domesticated animals, cereal cultivation, woodland clearance, more permanent settlement and the construction of ritual monuments (Cooney 2000; Whitehouse

et al. 2014). This was followed by an overall intensification of farming activity with metalwork aiding agricultural advancement during the Bronze Age (Grogan 2005; Waddell 2010). Neolithic farming in western Ireland was predominantly pastoral (Molloy and O’Connell 1995; Ghilardi and O’Connell 2013b; O’Connell et al. 2014), with evidence of Neolithic cattle dairying in the study region (Smyth and Evershed 2015). Arable farming in the Neolithic likely consisted of the cultivation of small, permanent plots of mostly wheat and barley (Whitehouse et al. 2014). Arable farming became more intensive during the Bronze Age as evidenced in a number of pollen records (Ghilardi and O’Connell 2013b; O’Connell et al. 2014).

Here, we explore the capabilities of chironomid analysis, combined with geochemical ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N) indicators, to investigate the environmental impacts of Neolithic and Bronze Age farming, through a comparative limnological assessment from three study sites in County Sligo, Ireland. A chironomid stratigraphy from Cooney Lough and new statistical analysis of recently published chironomid studies from Lough Dargan (Taylor et al. 2013) and Templevanny Lough (Taylor et al. 2016) are used to assess chironomid response to prehistoric land use change in the region. Select pollen and macroscopic charcoal data are used as markers of human activity, allowing for a multi-proxy investigation of the ecological impacts of prehistoric land use.

5.3 Site description

Cooney Lough is situated approximately 2 km west of Ballysadare, County Sligo, on a lowland coastal strip between Ballysadare Bay and the Ox Mountains (Fig. 5.1). It is a small lake (2.5 ha) of moderate depth (maximum = 8.3 m), which lies at an elevation of 36 m above sea level (a.s.l.). Further details on the bathymetry of the lake are available in O’Connell et al. (2014). The study site was chosen on account of its rich archaeological evidence from the Neolithic and Bronze Age. Carrowmore passage tomb cemetery has the greatest concentration of passage tombs (one of four major megalithic tomb types datable to the Neolithic) in Ireland (Bergh 1995; Bergh and Hensey 2013) and is located on Cúil Irra peninsula, about 4 km north of Cooney Lough. The early Neolithic causewayed enclosure of Magheraboy (Danaher 2007) is also located on the Cúil Irra peninsula, ~7 km from Cooney Lough. Several archaeological sites lie in close proximity (≤ 2.5 km) to the lake including a court tomb, passage tomb and *fulacht fia* (burnt mound - located close to the edge of the lake; [O’Connell et al. 2014]) (Fig. 5.1).

Comparative sites in this study include Lough Dargan and Templevanny Lough, County Sligo. Lough Dargan, a medium-size lake (10 ha, maximum depth 11.2 m) at 45 m a.s.l. is situated near Collooney, approximately 7 km east of Cooney Lough (Fig. 5.1b) (Ghilardi and O’Connell 2013b). The chironomid record from Lough Dargan spans 5690-730 BC (67 samples) (Taylor et al. 2013).

Templevanny Lough, a small lake (2 ha, maximum depth 6 m) at 84 m a.s.l., is located 21 km south of Cooney Lough in the fertile lowlands immediately west of the Bricklieve Mountains and the Carrowkeel-Keshcorran megalith-complex (Fig. 5.1b) (Stolze et al. 2013). The chironomid record from Templevanny Lough spans 4120-2480 BC (160 samples) (Taylor et al. 2016).

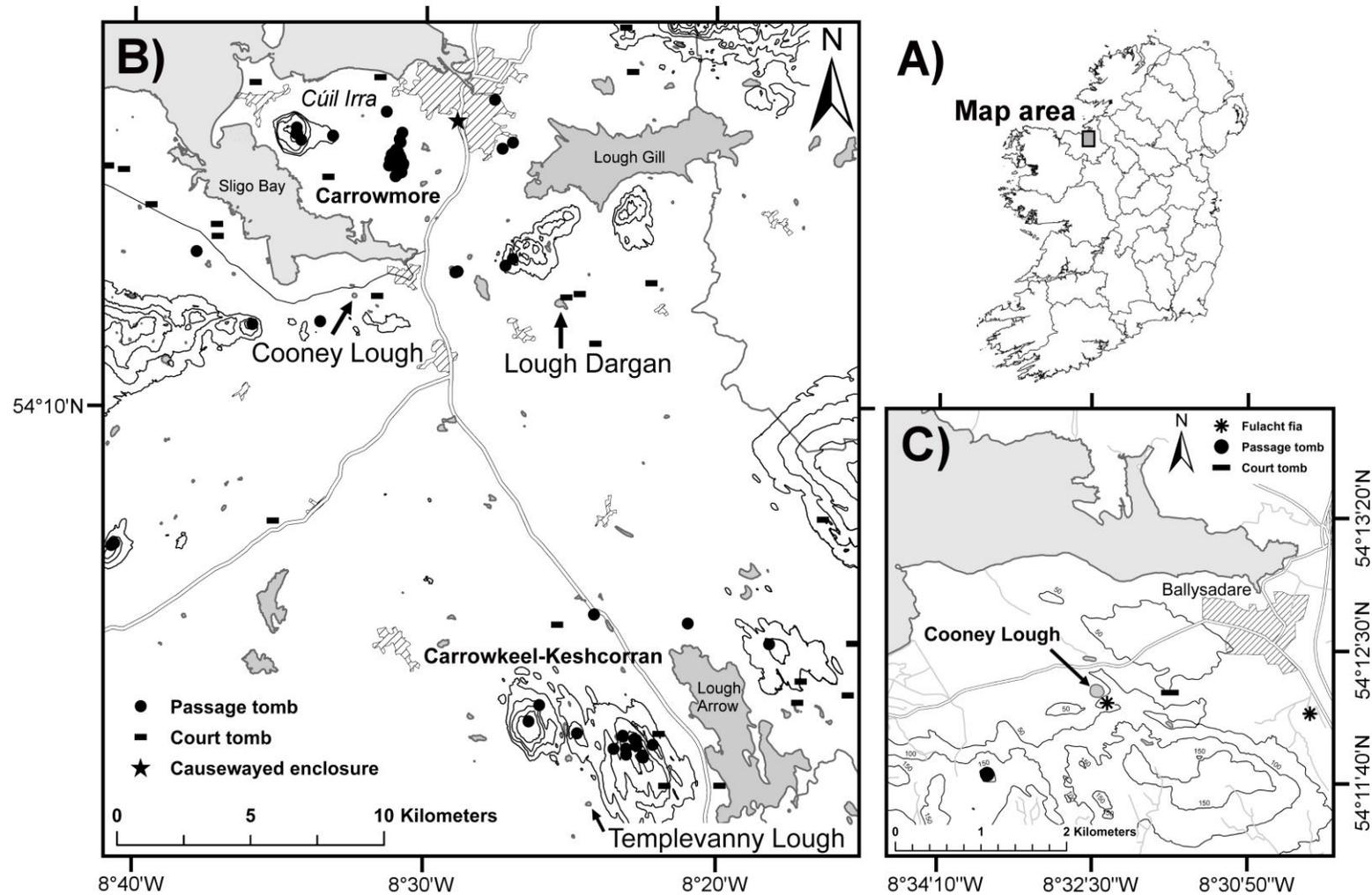


Fig. 5.1 - Maps showing the study region in northwest Ireland **(A)** with locations of the three study sites - Cooney Lough, Lough Dargan and Templevanny Lough **(B)**. Also included in **(B)** are major roads and towns, the Cúil Irra peninsula and the locations of the early Neolithic causewayed enclosure at Magheraboy, passage tombs of the Carrowmore and Carrowkeel-Keshcorran megalithic complexes and single court and passage tombs in the area. Elevation ranges from 150 to 400 m are denoted by contour lines at 50-m intervals. Map **(C)** shows Cooney Lough and the locations of a nearby court tomb, passage tomb and *fulacht fia* (contour interval is 50 m)

5.4 Materials and methods

5.4.1 Subsampling and radiocarbon dating

Cooney Lough was cored near the centre of the lake at a water depth of 8.3 m, using a Usinger piston corer fitted with a 2-m-long, 80-mm diameter, steel coring tube (O'Connell et al. 2014). Two parallel 6-m-long cores (CNY1 and CNY2) were extracted. Seventy-seven subsamples, 1 cm thick, were taken between 462 and 304 cm for chironomid, geochemical and macroscopic charcoal analyses, mainly from core CNY1. The break between core segments of CNY1 was bridged using sediment from the CNY2 core (O'Connell et al. 2014). Subsampling was carried out at intervals of 1 to 4 cm, with closer-interval sampling for part of the early Neolithic (427-421 cm). Eleven AMS ^{14}C dates were used to construct an age/depth model for Cooney Lough. Material for dating was obtained by taking 2-cm-thick slices with a wet weight of roughly 50 g. The samples were sieved through a 125- μm mesh and material of terrestrial origin was selected for ^{14}C AMS dating. The dates cited in this paper derive from the dating model in Ghilardi and O'Connell (2013a) and are expressed in calibrated years before present (BP), and rounded to the nearest 5 years.

5.4.2 Chironomid analysis

Chironomid analysis followed standard procedures outlined in Walker (2001). Between 0.75 and 3 cm^3 of wet sediment was deflocculated in a 10% KOH solution and heated for 30 minutes at 30°C. The sediment was then passed through a 90- μm mesh, and the resulting solution was poured into a Bogorov plankton counting tray. Samples were sorted under a Motic[®] SMZ Series dissection microscope (10-40x magnification). A minimum of 50 chironomid head capsules (mean = 65) per sample (Quinlan and Smol 2001) were removed with fine forceps and permanently mounted on slides with Entellan[®]. A Motic[®] B3 Professional Series compound microscope at 100-400x magnification was used for identification of chironomid subfossils. Taxa were identified to genus, sub-genus or species-type following Wiederholm (1983), Rieradevall and Brooks (2001), Brooks et al. (2007) and Larocque-Tobler (2014). A total of 95 taxa were identified in the Cooney Lough core, with 14 to 38 taxa (mean = 25) per sample. Chironomid ecology and distribution information are based largely on Brooks et al. (2007), Vallenduuk and Moller Pillot (2007) and Moller Pillot (2009, 2013).

5.4.3 Geochemical analyses ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N)

Stable isotope ratios of nitrogen ($\delta^{15}\text{N}$) and carbon ($\delta^{13}\text{C}$) and their elemental content (%N, %C and C:N) were analysed at the Isotope Biogeochemistry Laboratory, University of Hawai'i at Mānoa using

a Thermo Fisher Delta V Advantage EA-IRMS. Sediment samples of 1 cm³ were dried, pulverized with a mortar and pestle and sieved through a 200- μ m mesh. Following Harris et al. (2001), between 2 and 5 mg of homogenized material was weighed into silver capsules and HCl-fumigated and measured for $\delta^{13}\text{C}$ values. C:N ratios were calculated as the mass ratio of organic carbon to total nitrogen elemental concentrations. Isotope ratios are reported in per mil notation relative to the Vienna PeeDee Belemnite (VPDB) standard and atmospheric nitrogen for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, respectively. Stable isotope data have an accuracy and precision of better than $\pm 0.2\text{‰}$.

5.4.4 Macroscopic charcoal analysis

Macroscopic charcoal particles ($\geq 90 \mu\text{m}$) were counted concurrent with chironomid extraction. Macroscopic charcoal is reported as number of pieces per cubic centimetre (cm^{-3}) of wet sediment. Macroscopic charcoal generally reflects local fire activity, either natural or human-related (Whitlock and Larsen 2001; Hawthorne et al. 2016). For Cooney Lough, it is assumed that fire activity is human-related as there is a high positive correlation of microscopic charcoal and pollen indicators of human activity (O'Connell et al. 2014).

5.4.5 Pollen and loss-on-ignition analyses

Percentage curves for selected indicative pollen taxa, i.e. *Plantago lanceolata*, a pollen type used primarily as an indicator of pastoral farming in Europe (Behre 1981); cereal-type pollen ($\geq 40 \mu\text{m}$); total arboreal pollen (AP) and total non-arboreal pollen indicative of grassland/pasture (NAPp), are presented here, as in O'Connell et al. (2014). Loss-on-ignition (LOI) at 550 °C (LOI-2 curve in O'Connell et al. 2014) represents organic content as a percentage of dry weight (Heiri et al. 2001).

5.4.6 Statistical analyses

Ordination analyses were performed using Canoco version 5.04 (ter Braak and Šmilauer 2012) on square-root transformed chironomid percentage data for all common taxa, i.e. taxa present in at least two samples with a relative abundance of $\geq 2\%$ in at least one sample (Quinlan and Smol 2001). Both principal component analysis (PCA; linear model) and detrended correspondence analysis (DCA; unimodal model) were performed on the chironomid percentage data. A selection was made between linear and unimodal-based ordinations by assessing the gradient length (1.7 standard deviations (SD); linear model recommended) of the species composition along the first two axes (Birks 1995). PCA (percentage variance = 43.5%) also provided a better overall explanation of the

variance in the dataset than DCA (percentage variance = 32.7%). PCA Axis 1 was used to identify concurrent changes in the chironomid composition across all three study lakes.

The Shannon-Wiener diversity measure was calculated to assess diversity of the chironomid assemblages. The measure is defined as $H' = -\sum(p_i)(\ln p_i)$, where H' is the Shannon-Wiener index of diversity and p_i is the proportion of individual taxa in each sample. Both redundancy analysis (RDA; linear model) and canonical-correlation analysis (CCA; unimodal model) were performed, with RDA (explanatory variables accounted for 30.0% of variance) providing a better overall explanation of the variance in the data than CCA (explanatory variables accounted for 20.6% of variance) (Electronic Supplementary Table [ESM] S5.1). RDA was used to determine important environmental controls in the chironomid community composition for all three study lakes. For Lough Dargan, pollen and LOI values were interpolated to correspond with the chironomid and geochemical subsampling which was offset by 1 to 2 cm.

For each lake, the statistical significance ($p \leq 0.05$) of eight environmental variables ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N, NAPp, *Plantago lanceolata*, cereal-type pollen, macroscopic charcoal and LOI) was assessed using Monte Carlo permutation tests (499 unrestricted permutations) and P value correction, including the selected false discovery rate and the Bonferroni correction. Insignificant variables were dropped from further analysis. The remaining environmental variables were then forward-selected in order of decreasing variance, and selection continued as long as each additional variable remained a statistically significant predictor ($p \leq 0.05$) of chironomid assemblage data. Canonical coefficients, t-tests and eigenvalue ratios (λ_1/λ_2) for each of the forward-selected variables were used to identify important environmental controls in the chironomid assemblages. Partial RDAs were performed for common forward-selected variables across all study lakes ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N and NAPp) to identify dominant environmental controls in the region. For the RDA species biplots, taxa were only displayed if the particular taxon had a statistically significant relationship with either Axis 1 or Axis 2, although all common taxa at each site are included in the analyses. The level of significance was $p \leq 0.05$ for Lough Dargan and $p \leq 0.01$ for Cooney Lough and Templevanny Lough, to reduce overcrowding in the species biplots.

A chironomid percentage diagram was constructed using the program C2 version 1.7.6 (Juggins 2014). *Paratanytarsus* species-types and *Nanocladius* species-types were grouped together in Fig. 5.2 for explanatory and presentation purposes. *Paratanytarsus* is made up of *P.* undifferentiated and *P. penicillatus*-type; *Nanocladius* includes *N. branchicolus*-type and *N. rectinervis*-type. Zonation was performed with sum-of-squares partitioning on percentage chironomid data for all taxa, using psimpoll version 4.27 (Bennett 1993-2009). Chironomid-based

zones are used in the reporting of all data within each of the lake records to better understand major influences on chironomids through time.

5.5 Results

The Cooney Lough dataset spans the late Mesolithic to the late Bronze Age (5290-805 BC; 462-304 cm), with five statistically significant distinct zones, determined using chironomid percentage data (Fig. 5.2). Although subdivision of Zone 2 is not statistically significant, subzones were included to show notable qualitative changes during the Neolithic.

5.5.1 Zone 1 (5290-3760 BC; 462-431 cm)

The chironomid taxa *Chironomus anthracinus*-type and *Tanytarsus* undifferentiated (undif.) dominate Zone 1 (Fig. 5.2). *Tanytarsus* undif. abundance is relatively high, ranging from 6 to 25% with an average of 14%, while *Chironomus anthracinus*-type ranges from 0 to 21% with an average of 10%. *Tanytarsus lugens*-type, *Tanytarsus pallidicornis*-type, *Cladopelma* and *Polypedilum nubeculosum*-type are present in small numbers throughout this zone.

$\delta^{15}\text{N}$ values remain low, ranging from 1.6 to 2.5‰ (Fig. 5.3). C:N ratios average around 14.3 and LOI remains at roughly 84%. NAPp levels remain low throughout Zone 1, exhibiting an increase from 0.5 to 1% between 4965 and 4850 BC (456-454 cm) and a slight increase from 0.6% at 4200 BC (442 cm) to 1% by the end of the zone. Total arboreal pollen (AP) levels remain around 97%, with a slight decrease to 95% at 4850 BC (454 cm). Macroscopic charcoal shows a gradual increase, with peaks of 65 pieces cm^{-3} at 4850 BC (454 cm) and 150 pieces cm^{-3} at 3870 BC (434 cm).

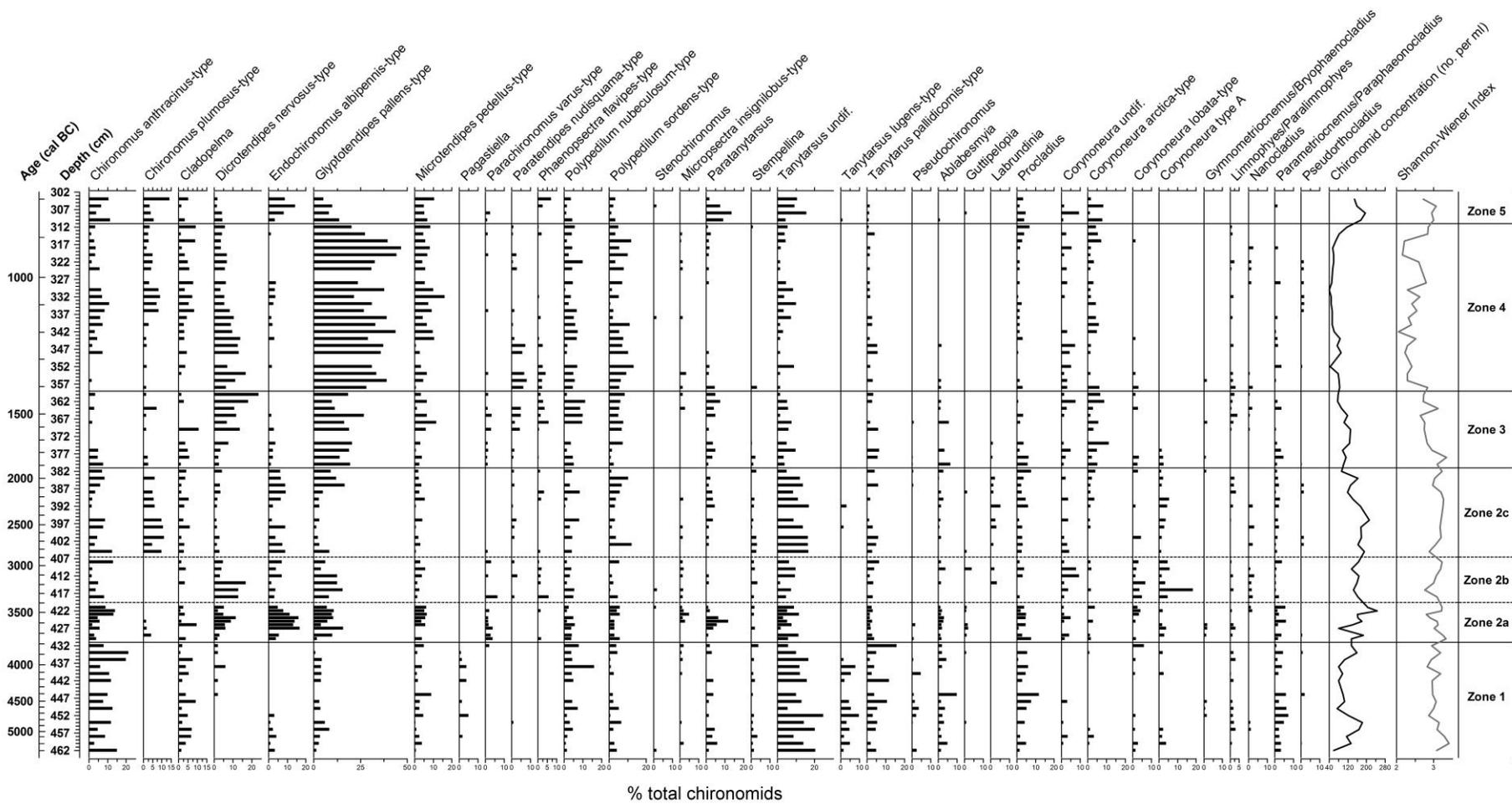


Fig. 5.2 - Chironomid percentage diagram from Cooney Lough including PCA Axis 1 and Shannon-Wiener diversity index

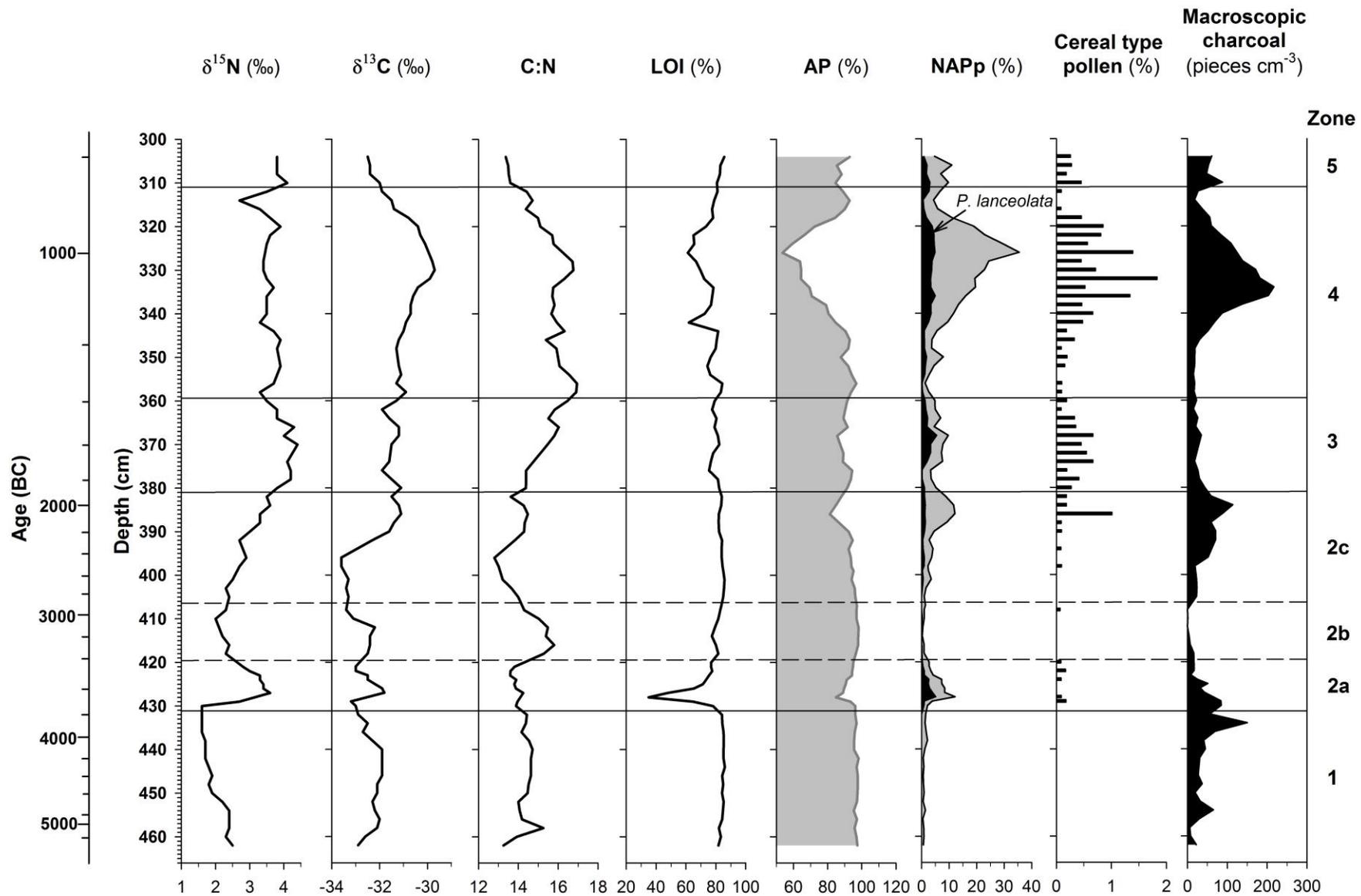


Fig. 5.3 - Geochemical data ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and C:N), LOI, selected percentage pollen curves (NAPp, *Plantago lanceolata*, cereal-type pollen and AP) and macroscopic charcoal curve from Cooney Lough

5.5.2 Subzone 2a (3760-3410 BC; 431-419.5 cm)

Chironomus plumosus-type appears in the chironomid record at 3700 BC (429 cm; 4%), but is only recorded in this subzone until 3580 BC (425 cm). *Endochironomus albipennis*-type (average 17%), *Glyptotendipes pallens*-type (average 16%) and *Dicretodipes nervosus*-type (average 6%) begin to increase in abundance from 3700 BC (429 cm) and peak at 3640 BC (427 cm), with continued presence through the remainder of Subzone 2a (Fig. 5.2). *Chironomus anthracinus*-type, *Polypedilum sordens*-type and *Polypedilum nubeculosum*-type are present throughout this subzone. *Gymnometriocnemus/Bryophaenocladus* is present at 3700 BC (429 cm; 1%), 3640 BC (427 cm; 2%) and 3610 BC (426 cm; 2%).

$\delta^{15}\text{N}$ values increase from 1.6 to 3.6‰ between 3730 and 3640 BC (430-427 cm), with values remaining roughly at 3.4‰ between 3640 and 3520 BC (427-423 cm) (Fig. 5.3). $\delta^{13}\text{C}$ values increase from -33.0‰ to -31.8‰ between 3730 and 3640 BC (430-427 cm). C:N ratios remain relatively stable at around 13.9, but with a slight decreasing trend. LOI values drop substantially from 78% to 35% between 3730 and 3670 BC (430-428 cm). Cereal-type pollen enters the stratigraphy at 3700 BC (429 cm; 0.2%) and averages 0.1% during this subzone. *Plantago lanceolata* increase in abundance from 1 to 5% between 3730 and 3670 BC (430-428 cm). NAPp increases substantially from 2 to 12% between 3730 and 3670 BC (430-428 cm) and averages 6% between 3670 and 3425 BC (430-420 cm). AP decreases from 96% to 85% between 3730 and 3670 BC (430-428 cm) and increases thereafter to 94%.

5.5.3 Subzone 2b (3410-2890 BC; 419.5-406.5 cm)

The previously dominant *Chironomus anthracinus*-type decreases from 8% to 2% between 3354 and 3125 BC (418-412 cm), but increases from 2 to 13% between 3040 and 2960 BC (410-408 cm). *Chironomus plumosus*-type is not recorded in this subzone (Fig. 5.2). *Endochironomus albipennis*-type decreases substantially, to an average of 5%. *Glyptotendipes pallens*-type continues at approximately 12% between 3355 and 3125 BC (418-412 cm), with percentages dropping to 4% by 3040 BC (410 cm). *Corynoneura undif.*, *Corynoneura lobata*-type and *Corynoneura* type A increase in abundance during this subzone, with a large increase in *Corynoneura* type A from 5 to 18% between 3355 and 3280 BC (418-416 cm).

$\delta^{15}\text{N}$ shows a decreasing trend, with values dropping from 2.4‰ to 2.0‰ between 3280 and 3040 BC (416-410 cm) (Fig. 5.3). C:N ratios increase to 15.8 by 3280 BC (416 cm). LOI remains at around 81% for Subzone 2b. NAPp, *Plantago lanceolata*, cereal-type pollen and macroscopic charcoal are in low abundance. NAPp values decline to roughly 0.9% between 3355 and 3280 BC

(418-416 cm) and reduce further to the lowest NAPp value of approximately 0.3% between 3205 and 3125 BC (414-412 cm). NAPp begins to increase to 1% by 3040 BC (410 cm). Macroscopic charcoal levels remain between 0 and 1 piece cm⁻³ from 3125 to 2960 BC (412-408 cm). AP values average 97%.

5.5.4 Subzone 2c (2890-1900 BC; 406.5-381 cm)

Tanytarsus undif. (average 13%), *Endochironomus albipennis*-type (average 7%), *Chironomus anthracinus*-type (average 6%) and *Chironomus plumosus*-type (average 6%) reappear as the predominant taxa (Fig. 5.2). *Chironomus plumosus*-type reappears in the stratigraphy at 2830 BC (405 cm; 10%) after a 590-year absence from the record between 3550 and 2960 BC (424-408 cm). *Dicrotendipes nervosus*-type and *Glyptotendipes pallens*-type occur in low abundances. Other taxa present include *Corynoneura* type A, *Limnophyes/Paralimnophyes*, *Paratanytarsus* and *Pseudorthocladius*.

$\delta^{15}\text{N}$ values show an increasing trend from 2.3 to 3.6‰ between 2740 and 2000 BC (403-384 cm) (Fig. 5.3). $\delta^{13}\text{C}$ remains at approximately -33.4‰ between 2830 and 2445 BC (405-396 cm) and increases thereafter to -31.2‰ by 2000 BC (384 cm). C:N decreases from 13.9 to 12.8 between 2830 and 2445 BC (405-396 cm), and increases to 14.0 by 2000 BC (384 cm). LOI averages 84%, with a slight decrease to 82% between 2210 and 2070 BC (390-386 cm). NAPp shows a general increasing trend, with peaks of 4% at 2655 BC (401 cm) and 2365 BC (394 cm), and a broad increase from 2290 to 1935 BC (392-382 cm) and a peak of 12% at 2070 BC (386 cm). *Plantago lanceolata* follows a similar pattern. Cereal-type pollen reappear in this zone from 0 to 1% between 2290 and 2070 BC (392-386 cm). AP shows a gradual decreasing trend from 95% to 81% between 2570 and 2070 BC (399-386 cm).

5.5.5 Zone 3 (1900-1380 BC; 381-359 cm)

Chironomus anthracinus-type and *Chironomus plumosus*-type abundances drop to an average of 3% and 2%, respectively (Fig. 5.2). *Dicrotendipes nervosus*-type steadily increases from 3 to 24% between 1870 and 1390 BC (380-360 cm). *Glyptotendipes pallens*-type is prominent (average of 18%) and displays a peak of 27% at 1510 BC (366 cm). *Polypedilum nubeculosum*-type, *Polypedilum sordens*-type and *Tanytarsus* undif. each average 5 to 6% abundance. *Corynoneura arctica*-type increases in abundance during this zone, with an average of 5%. *Gymnometriocnemus/Bryophaenocladius* is present at 1810 BC (378 cm) and again at 1555 BC (368 cm).

$\delta^{15}\text{N}$ is elevated during this zone with values ranging from 3.5 to 4.4‰ (Fig. 5.3). $\delta^{15}\text{N}$ peaks between 1810 and 1755 BC (378-376cm; approx. 4.2‰), at 1600 BC (370 cm; 4.4‰) and at 1510 BC (366 cm; 4.3‰). C:N ratios show an increasing trend from 14.4 to 16.5 between 1870 and 1395 BC (380-360 cm). NAPp values average 8% between 1700 and 1555 BC (374-368 cm), with a peak of 10% at 1555 BC (368 cm), concurrent with a *Plantago lanceolata* peak of 6%. Cereal-type pollen increase from an average of 0.3% between 1870 and 1755 BC (380-376 cm) to 0.6% between 1700 and 1555 BC (374-368cm).

5.5.6 Zone 4 (1380-870 BC; 359-311 cm)

Glyptotendipes pallens-type dominates Zone 4 with an average of 33% from 1360 to 875 BC (358-312 cm), with peaks in abundance of 44% at 944 BC (320 cm) and 47% at 927 BC (318 cm) (Fig. 5.2). *Chironomus anthracinus*-type reappears in the stratigraphy at roughly 6% between 1215 and 1030 BC (348-330 cm) and decreases thereafter. *Chironomus plumosus*-type also reappears in the record, increasing from 0 to 8% between 1105 and 1085 BC (338-336 cm). *Tanytarsus* undif. increases from 2% between 1360 and 1125 BC (358-340 cm) to 6% between 1105 and 1015 BC (338-328 cm). *Polypedilum sordens*-type, *Polypedilum nubeculosum*-type and *Cladopelma* are present throughout this zone. *Dicrotendipes nervosus*-type shows a gradual decreasing trend from 1300 to 930 BC (354-318 cm; 17% to 4%). The Shannon-Wiener diversity index shows a substantial decrease in the diversity of the chironomid assemblage during Zone 4.

$\delta^{15}\text{N}$ values remain relatively high between 1330 and 945 BC (356-320 cm), with values averaging 3.6‰ (Fig. 5.3). After the peak in $\delta^{15}\text{N}$ at 945 BC (320 cm; 3.9‰), values decrease to 2.7‰ by 890 BC (314 cm). $\delta^{13}\text{C}$ gradually increases, with values reaching their highest at 1070 to 945 BC (334-320 cm; -30.1‰). C:N increases from approximately 15.8 between 1145 and 1070 BC (342-334 cm) to roughly 16.6 between 1050 and 1015 BC (332-328 cm). NAPp increases from 1 to 8% between 1330 and 1240 BC (356-350 cm), and is followed by the largest increase in NAPp of 4 to 36% from 1190 to 995 BC (346-326 cm). *Plantago lanceolata* and cereal-type pollen follow a similar trend, with cereal-type pollen peaking at 1085 BC (336 cm; 1.3%), 1050 BC (332 cm; 1.8%) and 995 BC (326 cm; 1.6%), while *Plantago lanceolata* rises to 5% at 1090 BC (336 cm) and 1000 BC (326 cm). Macroscopic charcoal levels remain low (17 pieces cm^{-3}) from 1360 to 1215 BC (358-348 cm) and increase to 217 pieces cm^{-3} by 1070 BC (334cm).

5.5.7 Zone 5 (870-810 BC; 311-304 cm)

Chironomus anthracinus-type and *Chironomus plumosus*-type both increase from 4% at 840 BC (308 cm) to 11% and 14% by 805 BC (304 cm), respectively (Fig. 5.2). *Endochironomus albipennis*-type reappears in the stratigraphy and steadily increases from 3 to 14% between 860 and 825 BC (310-306 cm). *Tanytarsus undif.* increases to 12% between 840 and 805 BC (308-304 cm). The previously dominant *Dicrotendipes nervosus*-type and *Glyptotendipes pallens*-type decrease substantially through Zone 5.

$\delta^{15}\text{N}$ values display a peak of 4.1‰ at 860 BC (310 cm) (Fig. 5.3). $\delta^{13}\text{C}$ and C:N continue to decline from -31.9‰ to -32.5‰ and 14.4 to 13.4 from 875 to 805 BC (312-304 cm), respectively. NAPp values rise to 10% at 860 BC (310 cm) and again to 11% at 825 BC (306 cm). *Plantago lanceolata* and cereal-type pollen also increase during Zone 5. AP decreases to 85% at 860 BC (310 cm).

5.5.8 Redundancy Analysis (RDA)

The RDA for Cooney Lough produced eigenvalues for Axis 1 of 0.187 and for Axis 2 of 0.043, using five statistically significant forward-selected variables ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N, NAPp and LOI) (ESM Table S5.2). $\delta^{15}\text{N}$ showed the strongest relationship to RDA Axis 1 ($t = 9.83$), followed by C:N (8.52) and $\delta^{13}\text{C}$ (8.49). The samples bi-plot shows the chironomid community trajectory from a relatively unimpacted site during the Mesolithic to a more impacted site through the Neolithic and Bronze Age (Fig. 5.4a). There is a general trend of samples shifting towards the right of the bi-plot as NAPp, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and C:N all show a general increase through time. The species bi-plot shows that *Dicrotendipes nervosus*-type is associated with NAPp and high $\delta^{15}\text{N}$ values, and *Glyptotendipes pallens*-type is associated with high values of NAPp (Fig. 5.4a).

The RDA for Lough Dargan produced eigenvalues for Axis 1 of 0.194 and Axis 2 of 0.037, using four statistically significant forward-selected environmental variables ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N and NAPp) (ESM Table S2). $\delta^{15}\text{N}$ showed the strongest relationship with RDA Axis 1 ($t = -13.03$), followed by NAPp (-7.25). The RDA bi-plot shows the period 2380-730 BC is associated with high values of $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N and NAPp (Fig. 5.4b). The species bi-plot shows an association between *Chironomus plumosus*-type and high $\delta^{15}\text{N}$ values. *Glyptotendipes pallens*-type and *Paratanytarsus undif.* show a positive association with NAPp. *Sergentia coracina*-type shows a negative association with all forward-selected environmental variables.

The RDA for Templevanny Lough produced eigenvalues for Axis 1 of 0.095 and Axis 2 of 0.040, using six statistically significant forward-selected environmental variables ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N,

NAPp, LOI and macroscopic charcoal) (ESM Table S5.2). NAPp had the strongest relationship with RDA Axis 1 ($t = 20.53$), followed by macroscopic charcoal (12.43) and C:N (-11.56). $\delta^{15}\text{N}$ exhibited a strong relationship with RDA Axis 2 ($t = -15.87$). High values of NAPp are associated with chironomid samples from 3790-3610 BC (Fig. 5.4c). The species bi-plot highlights an association between *Tanytarsus lugens*-type and *Chironomus anthracinus*-type and high values of NAPp.

Partial RDAs show that $\delta^{15}\text{N}$ and NAPp are responsible for a significant proportion of the variance in the chironomid communities across all study lakes (Table 5.1). $\delta^{15}\text{N}$ exhibited the highest explanatory power at Cooney Lough, explaining 13.7% of the variance on its own and 9.5% with other variables partialled out. $\delta^{13}\text{C}$ (12.8% variance), C:N (12.7% variance) and NAPp (9.1% variance) also exhibited significant relationships with the chironomid data, although the relationships weakened when other variables were partialled out. At Lough Dargan, $\delta^{15}\text{N}$ exhibited the strongest relationship with the chironomid community, explaining 18.3% of the variance on its own and 8.3% with other variables partialled out. For Templevanny Lough, NAPp showed the strongest relationship with the chironomid community, explaining 8.6% variance on its own and 5.1% with other variables partialled out.

Figure 5.4

A) Cooney Lough

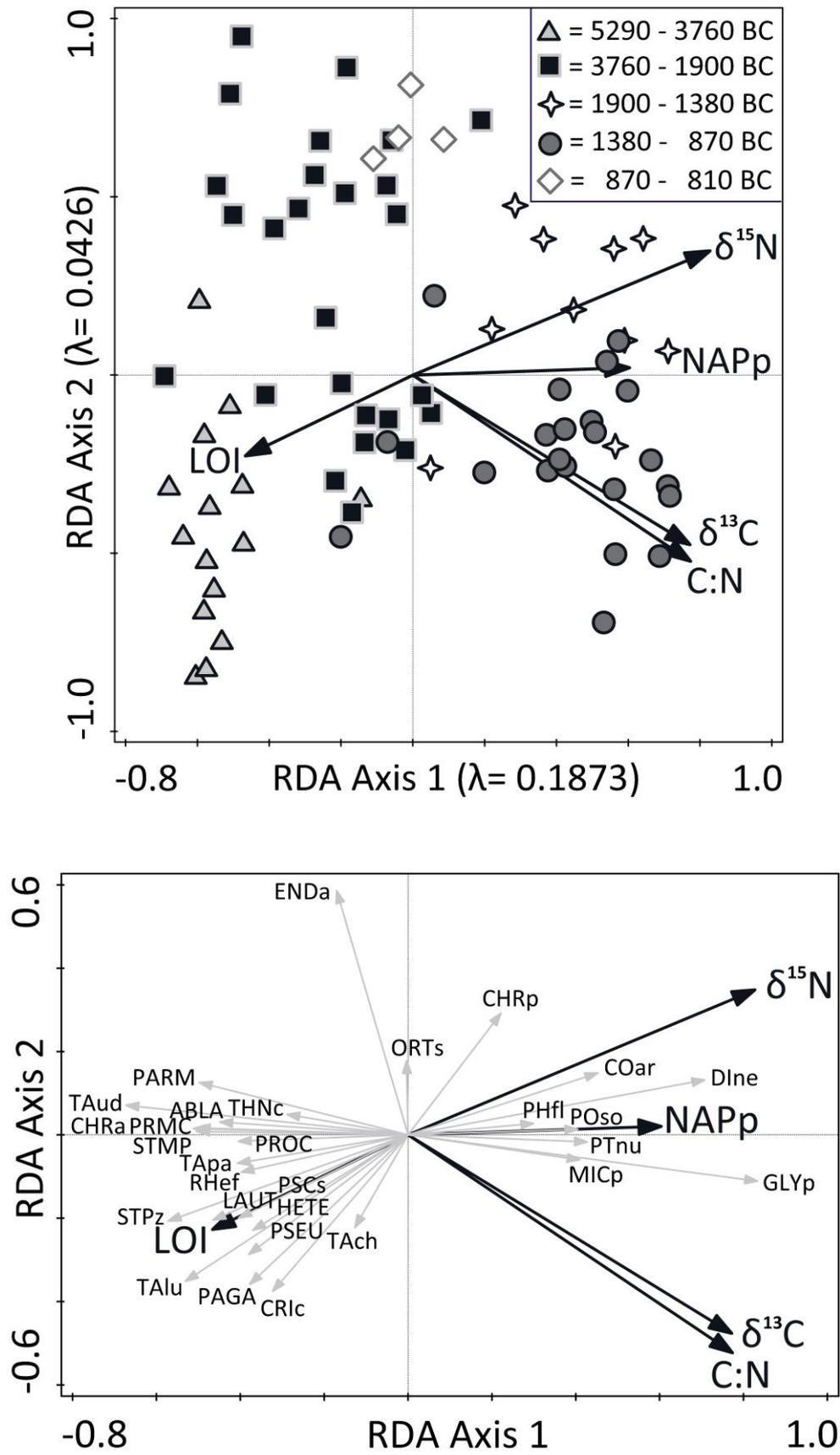


Figure 5.4

B) Lough Dargan

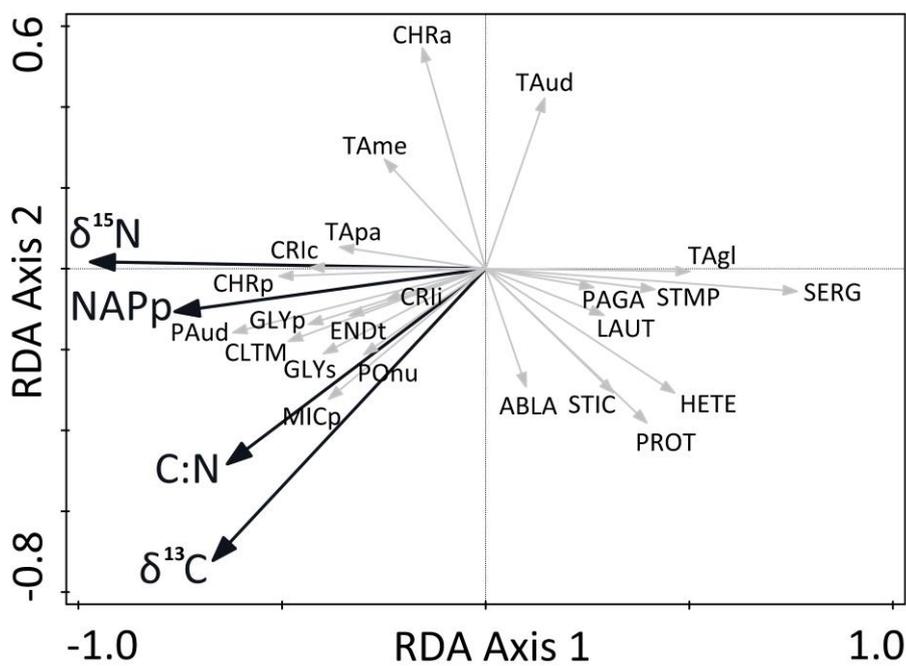
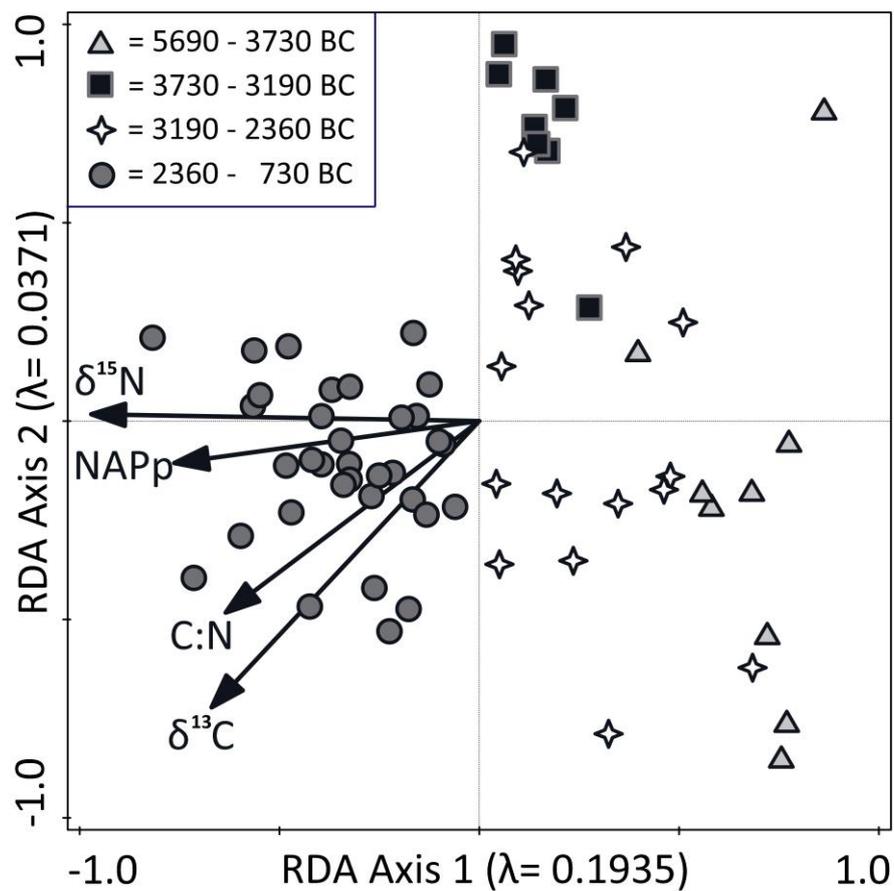


Figure 5.4

C) Templevanny Lough

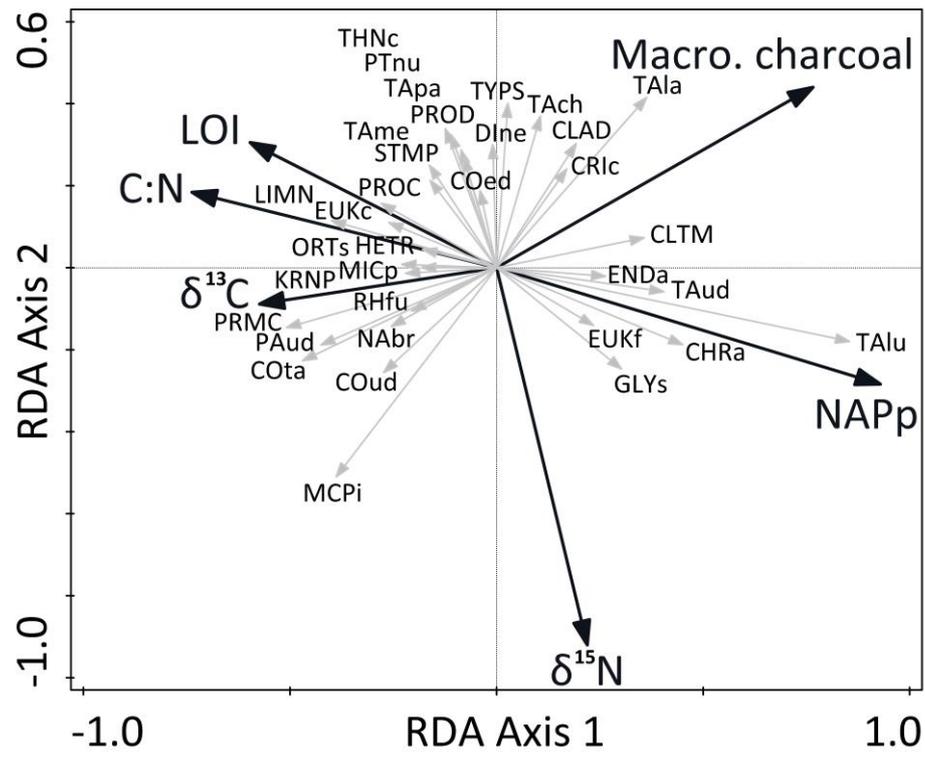
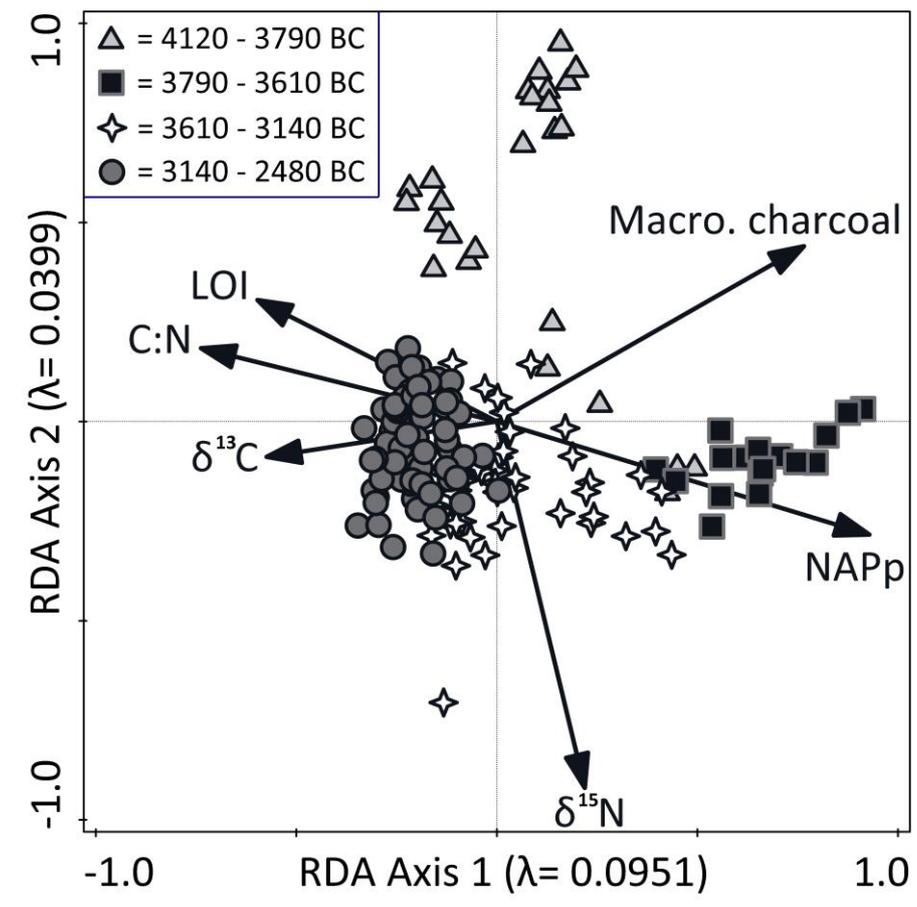


Fig. 5.4 - Redundancy analysis (RDA) of chironomid samples and species bi-plots with forward-selected environmental variables for **(A)** Cooney Lough, **(B)** Lough Dargan and **(C)** Templevanny Lough. For clarity, only taxa with a significant relationship ($p < 0.05$ for (B) or $p < 0.01$ for (A), (C)) to RDA Axis 1 or 2 are displayed in the figure. Symbols are used to denote chironomid-derived zonation for each lake. Legend: *Ablabesmyia* = ABLA, *Chironomus anthracinus*-type = CHRa, *Chironomus plumosus*-type = CHRp, *Cladopelma* = CLAD, *Cladotanytarsus mancus*-type = CLTM, *Corynoneura arctica*-type = COar, *Corynoneura edwardsi*-type = COed, *Corynoneura* type A = COta, *Corynoneura* undifferentiated = COud, *Cricotopus cylindraceus*-type = CRlc, *Cricotopus intersectus*-type = CRli, *Dicrotendipes nervosus*-type = DIne, *Endochironomus albipennis*-type = ENDa, *Endochironomus tendens*-type = ENDt, *Eukiefferiella claripennis*-type = EUKc, *Eukiefferiella fittkaui*-type = EUKf, *Glyptotendipes pallens*-type = GLYp, *Glyptotendipes severini*-type = GLYs, *Heterotanytarsus* = HETE, *Heterotrissocladius marcidus*-type = HETR, *Krenopelopia* = KRNP, *Lauterborniella* = LAUT, *Limnophyes/Paralimnophyes* = LIMN, *Micropsectra insignilobus*-type = MCPi, *Microtendipes pedellus*-type = MICp, *Nanocladius branchicolus*-type = NAb, *Orthocladius* type S = ORTs, *Pagastiella* = PAGA, *Parametriocnemus/Paraphaenocladius* = PRMC, *Paramerina* = PARM, *Paratanytarsus* undifferentiated = PAud, *Paratendipes nudisquama* = PTnu, *Phaenopsectra flavipes*-type = PHfl, *Polypedilum nubeculosum*-type = POnu, *Polypedilum sordens*-type = POso, *Prodiamesa* = PROD, *Protanypus* = PROT, *Psectrocladius sordidellus*-type = PSCs, *Pseudochironomus* = PSEU, *Procladius* = PROC, *Rheocricotopus effusus*-type = RHef, *Rheocricotopus fuscipes*-type = RHfu, *Sergentia coracina*-type = SERG, *Stempellina* = STMP, *Stempellinella/Zavrelia* = STPz, *Stictochironomus* = STIC, *Tanypus* = TYPS, *Tanytarsus chinyensis*-type = TAch, *Tanytarsus glabrescens*-type = TAgl, *Tanytarsus lactescens*-type = TAla, *Tanytarsus lugens*-type = TAlu, *Tanytarsus mendax*-type = TAm, *Tanytarsus pallidicornis*-type = TAp, *Tanytarsus* undifferentiated = TAud, *Thienemanniella clavicornis*-type = THNc

Table 5.1 - Partial RDAs of four common environmental variables ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N and NAPp) by themselves and with the effects of other environmental variables partialled out for each lake * $p < 0.05$

Variable	Covariable		Cooney Lough	Lough Dargan	Templevanny Lough
$\delta^{15}\text{N}$	None	λ_1	0.137	0.183	0.040
		λ_1/λ_2	1.079	1.794	0.357
		% variance	13.7*	18.3*	4.0*
	$\delta^{13}\text{C}$, C:N, NAPp	λ_1	0.075	0.066	0.040
		λ_1/λ_2	1.25	0.695	0.870
		% variance	9.5*	8.3*	4.5*
$\delta^{13}\text{C}$	None	λ_1	0.128	0.107	0.042
		λ_1/λ_2	0.901	0.560	0.483
		% variance	12.8*	10.7*	4.2*
	$\delta^{15}\text{N}$, C:N, NAPp	λ_1	0.031	0.031	0.016
		λ_1/λ_2	0.517	0.326	0.348
		% variance	4.2*	4.1*	1.9*
C: N	None	λ_1	0.127	0.096	0.059
		λ_1/λ_2	0.927	0.495	0.819
		% variance	12.7*	9.6*	5.9*
	$\delta^{15}\text{N}$, $\delta^{13}\text{C}$, NAPp	λ_1	0.055	0.024	0.015
		λ_1/λ_2	0.917	0.253	0.326
		% variance	7.2*	3.3*	1.8*
NAPp	None	λ_1	0.091	0.124	0.086
		λ_1/λ_2	0.52	0.747	1.323
		% variance	9.1*	12.4*	8.6*
	$\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N	λ_1	0.024	0.025	0.045
		λ_1/λ_2	0.4	0.263	0.978
		% variance	3.2*	3.4*	5.1*

5.6 Discussion

5.6.1 Cooney Lough

The paleoenvironmental data from the late Mesolithic to the beginning of the early Neolithic (5290-3760 BC) at Cooney Lough reflect a mesotrophic-eutrophic lake system with little to no human activity in the catchment area. The presence of mesotrophic taxa *Chironomus anthracinus*-type and *Cladopelma*, and eutrophic taxa *Tanytarsus pallidicornis*-type and *Polypedilum nubeculosum*-type (Brooks et al. 2007; Moller Pillot 2009), indicates a relatively productive lake system. Geochemical indicators corroborate the biotic data, with low C:N values providing further evidence of a naturally productive lake system (Cohen 2003). Low $\delta^{15}\text{N}$ values during this time are typical of regional lakes with little or no human activity in their catchments (Woodward et al. 2012). The pollen and macroscopic charcoal data provide little indication of human activity, with the exception of an early peak of macroscopic charcoal at 4850 BC, which coincides with a small decrease in AP and increases in NAPp, possibly suggesting early human disturbances or a natural forest fire.

The onset of early Neolithic farming is evident at Cooney Lough from 3700 BC, in the chironomid, pollen and geochemical data. The chironomid composition indicates a shift to more productive lake conditions, with the presence of mesotrophic-eutrophic taxa *Endochironomus albipennis*-type, *Glyptotendipes pallens*-type and *Dicrotendipes nervosus*-type (Moller Pillot 2009). The appearance of *Chironomus plumosus*-type further highlights a shift to more productive lake conditions, as *C. plumosus*-type is a eutrophic taxon that has been used as an indicator of hypereutrophic conditions in Danish lakes (Brodersen and Lindegaard 1999) and is an early coloniser in the profundal of highly eutrophic lakes (Moller Pillot 2009). The substantial increase in NAPp between 3670 and 3425 BC along with proportional increases in eutrophic chironomid taxa signify intensification of early Neolithic farming at Cooney Lough. An increase in $\delta^{15}\text{N}$ values at 3640 BC may be a consequence of increased agricultural inputs, as animal waste is high in ^{15}N (Woodward et al. 2012; Taylor et al. 2013; Botrel et al. 2014). Indicative eutrophic chironomid taxa also peak at this time and reduced C:N ratios provide evidence for increased productivity within the lake system (Cohen 2003). The steep drop in LOI at 3670 BC suggests increased minerogenic input and a peak in $\delta^{13}\text{C}$ values at 3640 BC suggests soil erosion, as terrestrial deposits typically have higher $\delta^{13}\text{C}$ values (Cohen 2003). This erosion event is supported by the geochemical evidence presented by O'Connell et al. (2014) and also coincides with records of the soil erosion indicator *Gymnometriocnemus/Bryophaenocladus* in the chironomid stratigraphy between 3700 and 3610 BC (Brooks et al. 2007).

A lull in farming activity occurred at Cooney Lough during the middle Neolithic (3410-2890 BC). This was contemporaneous with a decline in lake productivity, as reflected in the chironomid assemblage, with decreases in *Chironomus anthracinus*-type, *Chironomus plumosus*-type and *Endochironomus-albipennis*-type. Pollen, macroscopic charcoal and $\delta^{15}\text{N}$ data suggest a reduction of farming activity from 3355 to 3280 BC and an absence of farming from 3205 to 3125 BC. By 3040 BC, lake sediment geochemistry and chironomid community composition were similar to those found in the relatively un-impacted lake from the late Mesolithic to the beginning of the early Neolithic (5290-3760 BC).

The impact of small-scale late Neolithic and more intensive early Bronze Age farming in the catchment area from 2890-1900 BC is reflected in the chironomid composition, indicating a change to more productive lake conditions. The eutrophic taxon *Chironomus plumosus*-type dominates the stratigraphy along with mesotrophic-eutrophic taxa *Chironomus anthracinus*-type, *Tanytarsus* undif. and *Endochironomus albipennis*-type. This increase in eutrophic taxa coincides with a gradual increase in farming activity in the catchment area, as reflected in the pollen data. Increasingly positive $\delta^{15}\text{N}$ values together with relatively low $\delta^{13}\text{C}$ and C:N values suggest considerable nutrient enrichment from pastoral farming around the lakeside from 2830 to 2445 BC (Woodward et al. 2012; Botrel et al. 2014). Continued pastoral farming is evident from 2245 to 1900 BC, with increasing levels of $\delta^{15}\text{N}$ coinciding with a stepped increase in farming activity, as reflected in NAPp. The increased $\delta^{13}\text{C}$ and C:N from 2210 to 2000 BC and slight decrease in LOI suggest inwash of terrestrial material into the lake (Cohen 2003). An increase in *Limnophyes/Paralimnophyes* indicates a possible shift in lake level (Brooks et al. 2007), similar to that seen at Lough Dargan from 2710 to 2015 BC (Taylor et al. 2013), which coincides with a wet period in the region (O'Connell and Molloy 2001; Barber 2006).

Farming activity in the catchment area increased during the early and middle Bronze Age, particularly between 1700 and 1555 BC. Mesotrophic-eutrophic taxa *Dicrotendipes nervosus*-type, *Glyptotendipes pallens*-type, *Polypedilum nubeculosum*-type, *Polypedilum sordens*-type, *Tanytarsus* undif. and *Tanytarsus pallidicornis*-type increased in abundance in response to the increased farming activity. The Shannon-Wiener diversity index shows a decrease in the diversity of the chironomid assemblage, reflecting the dominance of *Dicrotendipes nervosus*-type and *Glyptotendipes nervosus*-type during this time. The increased cereal-type pollen suggests more arable farming, while high $\delta^{15}\text{N}$ values potentially show enhanced nutrient input. The increasing C:N ratios and presence of soil erosion indicator *Gymnometriocnemus/Bryophaenocladus* indicate increased inwash of terrestrial material.

A further shift in abundance of eutrophic taxa is evident from 1380 to 870 BC, during the middle to late Bronze Age, indicating a change to more productive lake conditions in response to farming activity. The Shannon-Wiener diversity index highlights a further decline in the diversity of the chironomid composition. The mesotrophic-eutrophic taxon *Glyptotendipes pallens*-type dominates the chironomid assemblage during this time with increased abundances following the largest peak of NAPp at 995 BC. Increased productivity is inferred from the presence of eutrophic taxa *Chironomus plumosus*-type, *Polypedilum nubeculosum*-type and *Polypedilum sordens*-type during this time. The pollen and macroscopic charcoal data highlight the most intensive period of pastoral and arable farming from 1190 to 890 BC. The relatively high $\delta^{15}\text{N}$ values at 1330-945 BC suggest high agricultural inputs or soil erosion. The increased values of $\delta^{13}\text{C}$ at 1070-945 BC along with increased C:N values from 1050 to 1015 BC potentially indicates deposition of terrestrial material in the lake. RDA analysis highlights the association between high values of NAPp, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and C:N and the chironomid assemblages between 1380 and 870 BC. This, together with the strong relationship between chironomids and $\delta^{15}\text{N}$ in the partial RDAs, provides evidence for farming activity being an important driving force behind chironomid community compositional change during the middle to late Bronze Age.

The chironomid composition during the late Bronze Age reflects renewed eutrophic conditions, with *Chironomus anthracinus*-type, *Chironomus plumosus*-type, *Endochironomus albipennis*-type and *Tanytarsus* undif. dominating the stratigraphy. This change in composition coincides with a small increase in pastoral and arable farming, as reflected in the NAPp, *Plantago lanceolata* and cereal-type pollen, and deforestation, as indicated by a decrease in AP. An increase in $\delta^{15}\text{N}$ similarly suggests another period of increased farming activity, while lower C:N ratios indicate increased lake productivity during this time.

5.6.2 Regional trends

Prehistoric farming activity directly impacted limnological conditions at all three lakes, with geochemical and chironomid responses following Neolithic and Bronze Age farming initiation and intensification. RDAs established pastoral farming proxies as important drivers of chironomid compositional change in all three lakes. Arable farming shows no measurable link with chironomids, and cereal-type pollen was not forward-selected in any of the RDAs because of its weak statistical relationship with chironomid assemblages. Lack of impact on the lake systems could reflect the scale of arable farming activities or the location of farming relative to the lakeside.

In all sites, early Neolithic pastoral farming is associated with increased $\delta^{15}\text{N}$ values, likely through direct inputs of ^{15}N -enriched animal waste (Woodward et al. 2012; Botrel et al. 2014) and/or

increased soil erosion (Kendall 1998; Talbot 2001) (Fig. 5.5). C:N ratios decrease in the early Neolithic as a consequence of increased lake productivity (Cohen 2003). Chironomid response follows, with an increase in eutrophic taxa at all sites, and a notable decrease in mesotrophic to oligotrophic taxa at Lough Dargan (Fig. 5.5). This was followed by a short-lived period of lake recovery at all three sites, expressed as a reduction in $\delta^{15}\text{N}$ values and eutrophic chironomid abundance during a farming lull in the middle Neolithic. The lull in farming activity can be seen throughout the region, as evident in pollen records (Ghilardi and O'Connell 2013b; Stolze et al. 2013; O'Connell et al. 2014; Whitehouse et al. 2014). The late Neolithic saw an increase in farming, with distinct periods of intensification during the Bronze Age. In the Bronze Age sediments from Cooney Lough and Lough Dargan, eutrophic taxa became even more prominent than during the early Neolithic, and $\delta^{15}\text{N}$, C:N and $\delta^{13}\text{C}$ values all increased, consistent with increased erosion and agricultural inputs during that time. Overall, the paleolimnological data showed more productive lake systems during periods of farming intensification, especially pastoral farming.

Within each lake record, $\delta^{15}\text{N}$ values vary with changes in pastoral pollen. In all three sites, $\delta^{15}\text{N}$ and NAPp were correlated, with Pearson's correlation coefficients of 0.516, 0.658 and 0.476 for Cooney Lough, Lough Dargan and Templevanny Lough, respectively. Woodward et al. (2012) found that $\delta^{15}\text{N}$ in modern lake sediments is greater in agriculturally active lake catchments, especially where cattle farming is prominent. Cooney Lough and Lough Dargan show higher $\delta^{15}\text{N}$ values during the Bronze Age than in the early Neolithic, with Cooney Lough and Lough Dargan showing averages of 3.0‰ (maximum of 3.6‰) and 3.3‰ (maximum of 3.7‰) during the early Neolithic and 3.7‰ (maximum of 4.4‰) and 4.2‰ (maximum of 5.1‰) during the Bronze Age, respectively (Fig. 5.5). $\delta^{15}\text{N}$ values during Neolithic and Bronze Age farming phases at all three sites would place these lakes among moderately impacted lakes in western Ireland today (Woodward et al. 2012).

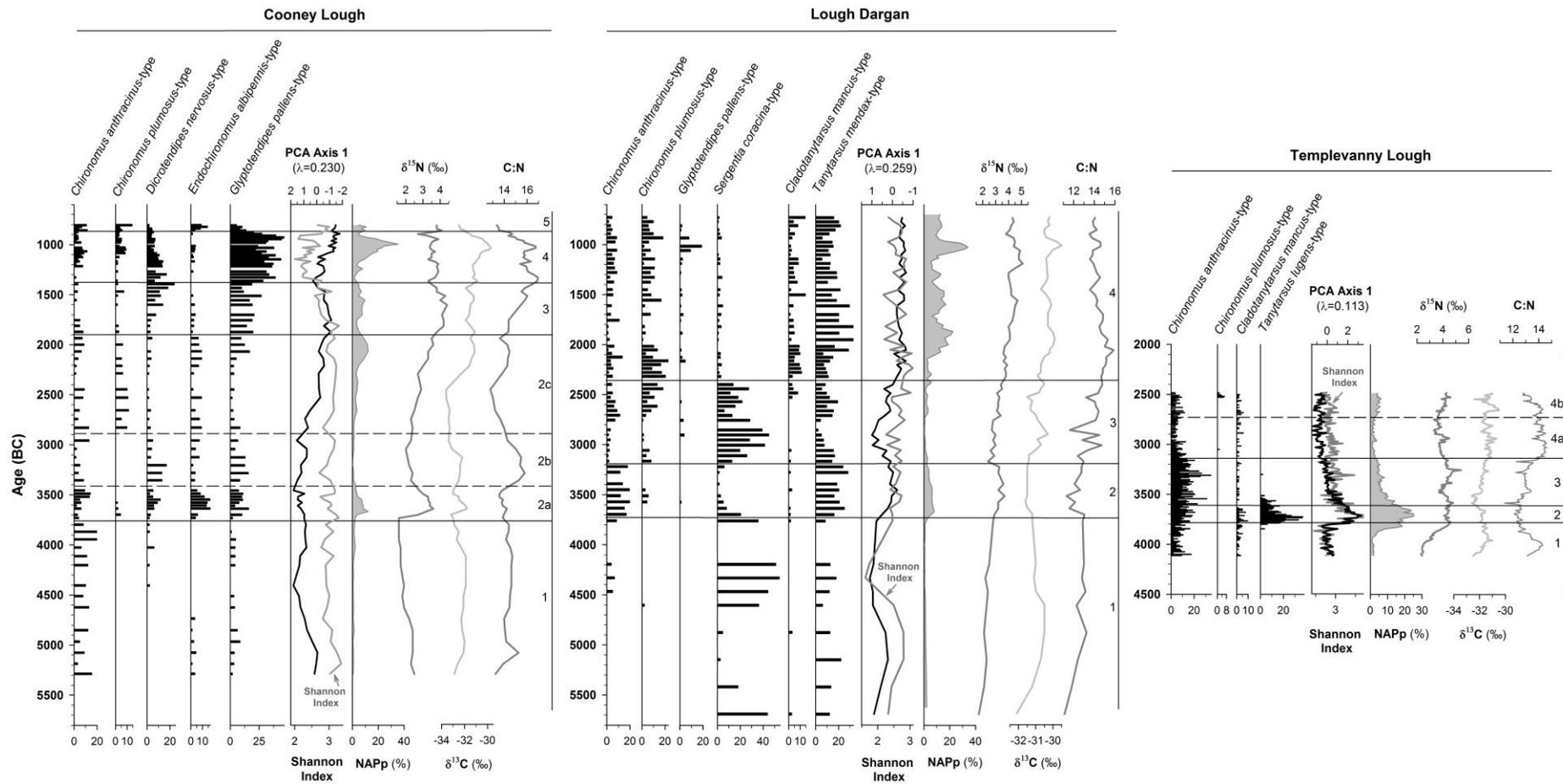


Fig. 5.5 Composite diagram for Cooney Lough, Lough Dargan and Templevanny Lough, including chironomid percentages for the main responsive taxa, chironomid PCA Axis 1, Shannon-Wiener diversity index, and common forward-selected environmental variables ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N and NAPp) at each study lake

5.6.3 Chironomid response

Chironomid response within the three study lakes appears to be roughly proportional to the scale of agricultural activities, as evidenced from shifts in PCA Axis 1 scores and Shannon-Wiener diversity indices (Fig. 5.5). Although increases in eutrophic taxa may be expected, specific taxon response varies between sites. *Chironomus plumosus*-type is the common eutrophic taxon that appears in all three lakes in response to nutrient enrichment associated with late Neolithic and Bronze Age farming. This is not surprising as *C. plumosus*-type is regarded as a eutrophic to hypereutrophic profundal taxon and a pioneer species (Moller Pillot 2009). *Chironomus anthracinus*-type, *Dicrotendipes nervosus*-type, *Endochironomus-albipennis*-type and *Glyptotendipes pallens*-type are the main taxa at Cooney Lough that exhibit a response to farming. *Chironomus anthracinus*-type, *Glyptotendipes pallens*-type, *Cladotanytarsus mancus*-type and *Tanytarsus mendax*-type are the main responsive taxa at Lough Dargan, and *Chironomus anthracinus*-type, *Cladotanytarsus mancus*-type and *Tanytarsus lugens*-type are the main responsive taxa at Templevanny Lough. Each of these taxa is either associated with agriculturally active lake catchments in western Ireland today (Potito et al. 2014), or has been associated with productive mesotrophic-eutrophic lake systems (Moller Pillot 2009), and/or hypereutrophic conditions in other regions of Europe (*Chironomus plumosus*-type and *Glyptotendipes*; Brodersen and Lindegaard 1999).

Lake-specific differences were noted in the chironomid response to farming activity within the region. Chironomid response to farming is more visible at Lough Dargan than at the other two sites. The heightened response at Lough Dargan is mainly a consequence of the natural pre-impacted state of the lake. Lough Dargan was less productive than the other two sites during the Mesolithic, and the chironomid community was dominated by *Sergentia coracina*-type, a mesotrophic to oligotrophic taxon (Brooks et al. 2007; Moller Pillot 2009) (Fig. 5.5). The onset of farming saw a major reduction in this taxon and an increase in eutrophic taxa. Although farming impact was apparent at the other two sites, the changes were more subtle as eutrophic taxa were prominent prior to the introduction of farming.

Findings from Templevanny Lough highlight the importance of assessing intensity and longevity of farming activity in the catchment. At Templevanny Lough the lower eigenvalues and percentage variance found in the RDA and partial RDAs suggest a weaker relationship between environmental variables associated with farming activity and chironomid community composition. This is a consequence of the large sample size (160 samples), the duration of the interval that is being studied (4120-2480 BC), and longevity/intensity of human impact. The main period of Neolithic farming activity at Templevanny Lough spans roughly 27 samples (3820 - 3560 BC) of the total 160.

The timing and magnitude of changes in the chironomid assemblages in relation to farming indicators, as well as the results of RDAs, establish prehistoric pastoral farming practices as a significant control on the chironomid communities at all three study sites, with periods of farming activity regularly causing lake eutrophication. Stolze et al. (2013) show a close relationship between climate and Neolithic farming activity in the study region, suggesting that climate change could have an indirect (as well as direct) impact on chironomid assemblages in the study lakes. The subdued Holocene temperature range in Ireland (Swindles et al. 2013), suggests that climate alone is unlikely to have driven the substantial shifts in chironomid communities during periods of Neolithic and Bronze Age farming. Determination of the controlling factors behind chironomid compositional change can prove difficult, as problems can arise when dealing with multiple stressors (North et al. 2013). Brooks et al. (2012) highlighted several examples of studies in which local human activities strongly affected the nutrient enrichment of lake systems and led to shifts in trophic status unaffected by climate (Heiri and Lotter 2003, 2005; Gathrone et al. 2007). These studies show that human impact can be discerned and isolated from climate responses in chironomid records (Brooks et al. 2012). Furthermore, McKeown and Potito (2016) demonstrated that moderate human impacts are sufficient to over-ride the climate signal in a chironomid-inferred temperature reconstruction of the late nineteenth to early twenty-first centuries in Ireland.

5.7 Conclusions

This study highlights the utility and advantages of using chironomids in multi-proxy paleolimnological studies to better understand environmental impacts of prehistoric farming practices. Results can be used to gauge land use intensity, scale of activities and/or proximity of farming activity to the lakeside. The timing and magnitude of change shows that farming exhibited a strong control over diversity and abundance of chironomid communities through the Neolithic and Bronze Age in all of the study sites. The importance of pastoral farming to changes in lake ecology was demonstrated, and thus needs to be considered when attempting chironomid-based Holocene reconstructions in Ireland and other regions. The multi-proxy approach employed here provided substantial new information on the nature and intensity of farming during the Neolithic and Bronze Age in northwest Ireland, and enabled detailed reconstruction of nutrient influx and lake response to early farming. Furthermore, the study demonstrated the importance of chironomid analysis, especially in studies for which holistic reconstructions of farming impact are required.

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Model Statistics	<i>Cooney Lough</i>	<i>Lough Dargan</i>	<i>Templevanny Lough</i>
Number of samples	77	67	160
Number of common taxa	60	44	81
<i>RDA</i>			
Sum of squares	2679.70	1844.15	6243.52
R ²	30.0	27.3	17.9
R ² (adj)	25.1	22.6	14.7

Electronic supplementary material [ESM] Table S5.1 - Summary and performance statistics for significant environmental variables relating to the chironomid distributions at Cooney Lough, Lough Dargan and Templevanny Lough. Analysis was performed on common taxa for each lake, i.e. taxa present in at least two samples with a relative abundance of $\geq 2\%$ in at least one sample

	Cooney Lough				Lough Dargan				Templevanny Lough			
	Axis 1	Axis 2	Axis 3	Axis 4	Axis 1	Axis 2	Axis 3	Axis 4	Axis 1	Axis 2	Axis 3	Axis 4
<i>PCA - Full Model</i>												
Eigenvalue	0.230	0.087	0.073	0.045	0.114	0.059	0.049	0.037	0.259	0.083	0.066	0.060
Cum % var. spp.	23.0	31.7	39.0	43.5	11.4	17.4	22.3	26.0	25.9	34.2	40.8	46.8
<i>RDA - Full Model</i>												
Eigenvalue	0.187	0.043	0.042	0.015	0.194	0.037	0.032	0.011	0.095	0.040	0.021	0.013
Pseudo-canonical corr.	0.907	0.745	0.783	0.743	0.876	0.753	0.722	0.665	0.918	0.852	0.703	0.714
Cum % var. spp.	18.7	23.0	27.2	28.8	19.3	23.1	26.2	27.3	9.5	13.5	15.6	16.9
<i>Canonical coefficients</i>												
$\delta^{15}\text{N}$	0.750	0.260	0.173	-0.163	-0.850	0.013	-0.014	0.159	0.202	-0.784	-0.013	0.186
$\delta^{13}\text{C}$	0.700	-0.354	0.308	0.088	-0.587	-0.543	0.120	0.036	-0.527	-0.076	0.470	-0.088
C:N	0.702	-0.389	-0.205	0.074	-0.556	-0.364	-0.359	-0.227	-0.677	0.157	0.143	-0.438
NAPp	0.547	0.015	0.545	0.221	-0.669	-0.080	0.409	-0.194	0.853	-0.242	0.124	0.052
LOI	-0.423	-0.169	-0.061	-0.620	-	-	-	-	-0.548	0.260	-0.260	-0.392
Macroscopic charcoal	-	-	-	-	-	-	-	-	0.703	0.375	0.035	-0.124
<i>T-values</i>												
$\delta^{15}\text{N}$	9.83*	2.33*	1.52	-1.43	-13.03*	-0.10	-0.11	1.30	2.59*	-15.87*	-0.16	2.38*
$\delta^{13}\text{C}$	8.49*	-3.28*	2.81*	0.76	-5.84*	5.22*	0.98	0.29	-7.79*	-0.96	6.69*	-1.12
C:N	8.52*	-3.66*	-1.81	0.64	-5.39*	-3.15*	-3.10*	-1.88	-11.56*	2.00	1.81	-6.13*
NAPp	5.66*	0.13	5.62*	1.96	-7.25*	-0.65	3.62*	-1.60	20.53*	-3.14*	1.58	0.65
LOI	-4.05*	-1.49	-0.53	-6.84*	-	-	-	-	-8.23*	3.39*	-3.39*	-5.36*
Macroscopic charcoal	-	-	-	-	-	-	-	-	12.43*	5.09*	0.44	-1.57

Electronic supplementary material [ESM] Table S5.2 - Principal component analysis (PCA) and redundancy analysis (RDA) summary statistics, canonical coefficients and t-values for forward selected variables at Cooney Lough, Lough Dargan and Templevanny Lough. Pseudo-canonical corr. = Pseudo-canonical correlation for each axis. Cum % var. spp. = cumulative percent variance in species data for each axis. Significant t-values are shown in bold * $p < 0.05$

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Chapter 6 - Paper Three

“A chironomid-inferred temperature record for Irish prehistory from northwest Ireland”

A chironomid-inferred temperature record for Irish prehistory from northwest Ireland

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6.1 Abstract

This study provides the first mid to late Holocene chironomid-inferred temperature (C-IT) model for Ireland, creating a valuable climatic context for the development of Irish society during the Neolithic and Bronze Age. Using a lake sediment core from an isolated catchment in northwest Ireland, a multi-proxy approach of chironomid (Diptera: Chironomidae) subfossils, sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N) and pollen analysis was used to assess any potential limnological impact from prehistoric human activity in the region and provide a quantitative summer temperature estimate for the late Mesolithic to the Iron Age (7020 - 2050 cal yr BP). The pollen record provides a local signal of human activity, showing low levels of pastoral indicators in the early Neolithic, with increased evidence for pastoral and arable farming during the Bronze Age and in particular the Iron Age. Human activity does not appear to be a driving force in lake system change at L. Meenachrinna, as peaks in farming indicators (e.g. pastoral pollen indicators and increased $\delta^{15}\text{N}$ values) were not concurrent with major fluctuations in the chironomid assemblages, and were not identified as predominant controlling factors in RDA analysis. C-ITs provide evidence of multiple fluctuations in temperature during the mid to late Holocene with a drop of 0.7 °C during the late Mesolithic from 6550 - 6190 cal yr BP, and a warming phase during the early Neolithic period from 5800 - 5620 cal yr BP. C-IT reflect a relatively stable climate during the middle to late Neolithic, followed by a cold event at 3470 cal yr BP, a later warm phase at 3230 cal yr BP and a brief decline in temperatures of 1.3 °C at 2430 cal yr BP during the Iron Age.

Keywords: Neolithic, Bronze Age, Holocene, Stable Isotopes, Pollen, Multi-proxy

6.2 Introduction

Irish Holocene temperature variability is relatively subdued, although recent palaeoclimatic reconstructions show evidence of important small-scale climatic fluctuations and abrupt climatic events in Ireland during this time (Caseldine et al., 2005; Stolze et al., 2013; Swindles et al., 2013). Climatic reconstruction of the Neolithic (5950 - 4450 yr BP) and Bronze Age (4450 - 2750/2700 yr BP) is particularly valuable for Ireland, as they mark important developments of prehistoric human society (Becker et al., 2009; Cooney, 2000). Cultural changes include the transition from Mesolithic hunter-fisher-gatherer societies to Neolithic farming-based economies and the advancement of prehistoric societies into the Bronze Age (Cooney, 2000; Grogan, 2005; Waddell, 2010; Whitehouse et al., 2014). The role of climate and its potential influence on the development of society has been frequently debated (Armita et al., 2014; Magny, 2004; Mayewski et al., 2004; Stolze et al., 2013; Turney et al., 2006), but still remains unclear due to the lack of an independent temperature record for Ireland during this time.

The majority of Holocene palaeoclimatic research in Ireland has been acquired through peatland reconstructions (palaeohydrology using peat humification, testate amoebae and plant macrofossil analysis), and dendrochronology, providing information on effective moisture (Barber et al., 2003; Caseldine et al., 2005; Langdon et al., 2012; Swindles et al., 2007; Turney et al., 2006). Swindles et al. (2013) highlight the need for more biological proxies in Irish Holocene climate reconstructions including diatoms, cladocera and chironomids. At present, chironomid-inferred Holocene temperature reconstructions in Ireland include two late glacial to early Holocene records (Watson et al., 2010; van Asch et al., 2012) and a record from the recent past (last 150 years; McKeown et al., 2016).

Chironomid (Diptera: Chironomidae) subfossils are a versatile biological indicator in both paleotemperature and palaeoenvironmental studies, due to their worldwide distribution and abundance, mobility and sensitivity to changing limnological conditions (Brooks et al., 2007; Vallenduuk and Moller Pillot, 2013; Walker, 2001). As chironomids are affected by a variety of environmental variables (Eggermont and Heiri, 2012), chironomid reconstructions in Ireland can be impacted by relatively dense human settlement and active farming since the Neolithic (Cooney 2000). For example, prehistoric pastoral farming has been shown to have a significant impact on chironomid communities at multiple sites, rich in archaeological evidence from the Neolithic and Bronze Age in northwest Ireland (Taylor et al., 2017a, 2017b, 2013). McKeown et al. (2016) also highlight the influence of moderate land-use on a chironomid-inferred temperature record in northwest Ireland, and emphasise the need for pollen analysis to accompany chironomid-based temperature reconstructions to identify land-use change within the catchment.

This study aims to develop the first independent chironomid-inferred temperature record for the mid to late Holocene in Ireland, using a lake sediment core from an isolated catchment (i.e. isolated from archaeological evidence of prehistoric settlement) in northwest Ireland. A multi-proxy approach of chironomid, sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N) and pollen analysis will be used to assess any potential limnological impact from human activity in the region and provide a quantitative summer temperature estimate for the late Mesolithic to the Iron Age.

6.3 Study site

Lough Meenachrinna (54°43'41.8"N, 8°40'45.5"W) is located in the *Chruach an Chuilinn* mountains 4 km northeast of the village of *Gleann Cholm Cille* (Glencolmcille), County Donegal, Ireland (Fig. 6.1). It is a small (3.6 ha), high elevation (286 m a.s.l.) lake, with a maximum water depth of 7.3 m. A small sand deposit is present on the northeastern side of the lake, approximately 20 m long by 5 m wide. The lake is situated on the Precambrian, Slieve Tooye Quartzite formation (Geological Survey of Ireland, 2013), and the surrounding catchment vegetation is dominated by blanket bog and heathland.

Lough Meenachrinna was chosen for this palaeoenvironmental reconstruction on account of its remote upland location, along the northwestern edge of Ireland. The immediate lake catchment shows no archaeological evidence of human activity from the Neolithic to Iron Age. However, several prehistoric and more recent monuments are present at <20 m a.s.l. in the *Gleann Cholm Cille* valley, south of the lake (Fig. 6.1). Three megalithic tombs are recorded in the valley, providing the earliest evidence for settlement (see www.archaeology.ie). These include a Neolithic court tomb (DG-80-34-00) and an unclassified tomb (DG-80-13-01) located on the central ridge in the western part of the valley. The remains of Ireland's largest central court tomb (DG-80-60-00) are located at the bottom of *Chruach an Chuilinn* mountain on the northern side of the valley. Settlement evidence from the Bronze Age is represented by the presence of a standing stone (DG80-24-05) and ring-cairn (DG80-31-00) to the south, and an inland promontory fort (DG81-10-00) to the east-southeast. The final identifiable pre-Christian monument type is a late prehistoric ring-barrow (DG80-18-00) situated on the central ridge.

Ireland's climate is strongly influenced by the North Atlantic circulation which provides a temperate maritime climate with relatively few extremes in temperature. A climate station at Ballyshannon, County Donegal (40 km from the study site), shows an average July air temperature of 14.4 °C in 2017, and an average January air temperature of 6.6 °C (Met Éireann, 2017a). Atlantic fronts, primarily from the west and southwest, provide ample rainfall in western Ireland; averaging between 1000 - 1400 mm yr⁻¹ with a higher rainfall in mountainous areas (Met Éireann, 2017b).

6.4 Methodology

6.4.1 Sediment core

In the summer of 2013, two parallel off-set sediment cores (DL-LM-A and DL-LM-B) were extracted, in 1 m drives, from the deepest part of L. Meenachrinna using a Livingstone piston corer. The top section of core B (0 - 64 cm) was sectioned in the field at 1-cm intervals. The lower sections (DL-LM-A 62 - 192 cm; DL-LM-B 65 - 160 cm) were extruded on site, wrapped and later sectioned at 1-cm intervals at National University of Ireland Galway (NUIG). Core DL-LM-B was used for all analyses.

6.4.2 Dating model

Ten samples for AMS ^{14}C dating were submitted to the $^{14}\text{CHRONO}$ Centre, Queen's University, Belfast (Table 6.1). Both bulk sediment and hand-picked plant macrofossils were used for dating. Plant macrofossils were isolated by sieving 1-cm-thick slices of sediment through a 125- μm mesh to obtain material of terrestrial origin for dating. Bacon version 2.2 (Blaauw and Christen, 2011), which utilises IntCal13 (Reimer et al., 2013), was used to construct a Bayesian age/depth model for L. Meenachrinna (Fig. 6.2). Markov-chain Monte Carlo (MCMC) iterations for the model are as follows: accumulation shape = 1.5, accumulation mean = 50 years/cm, memory strength = 4, memory mean = 0.7. Eight samples produced reliable ages, with two samples removed from the dating model following biomarker verification of the Elm Decline (accepted date of c. 5800 yr BP; O'Connell and Molloy, 2001). All dates produced by Bacon are expressed in calibrated years before present (cal yr BP) and rounded to the nearest 10 years. The division of the Irish prehistoric period is based on Cooney (2000), O'Brien (2016) and Becker et al. (2009).

Table 6.1 - ^{14}C dates for the DL-LM-B core including material description¹.

Lab No.	Sample ID	Depth (cm)	Material description	^{14}C Age (yr BP)	±	Age range (2 σ , 95.4%) (cal yr BP)	Comments
UBA-24069	DL-LM-B-12.5	12.5	Twig	75	28	139 - 30	Accepted
UBA-24070	DL-LM-B-48.5	48 - 49	Bulk sediment	1767	27	1741 - 1603	Accepted
UBA-24422	DL-LM-B-59.5	59 - 60	Bulk sediment	2452	28	2544 - 2363	Accepted
UBA32786	DL-LM-B-70	70 - 71	Charcoal, charred <i>Calluna</i> stems, leaves and flowerheads	2896	30	3084 - 2949	Accepted
UBA-24071	DL-LM-B-82	82	Twig	4302	35	4895 - 4831	Accepted
UBA-33811	DL-LM-B-85	85 - 86	Charcoal and wood fragments; plant remains including <i>Calluna</i>	4802	33	5558 - 5472	Rejected* ²
UBA-24423	DL-LM-B-89.5	89 - 90	Bulk sediment	5067	30	5904 - 5744	Rejected* ²
UBA-24072	DL-LM-B-100.5	100.5	Twig	4634	38	5468 - 5300	Accepted
UBA-24424	DL-LM-B-111.5	111 - 112	Bulk sediment	5472	31	6312 - 6210	Accepted
UBA-24073	DL-LM-B-120.5	120 - 121	Bulk sediment	6581	39	7521 - 7428	Accepted

¹ 2-sigma range refers to the largest relative area under probability distribution in IntCal13.14c (Reimer et al., 2013).

² *Denotes rejected dates, using biomarker verification of the Elm Decline.

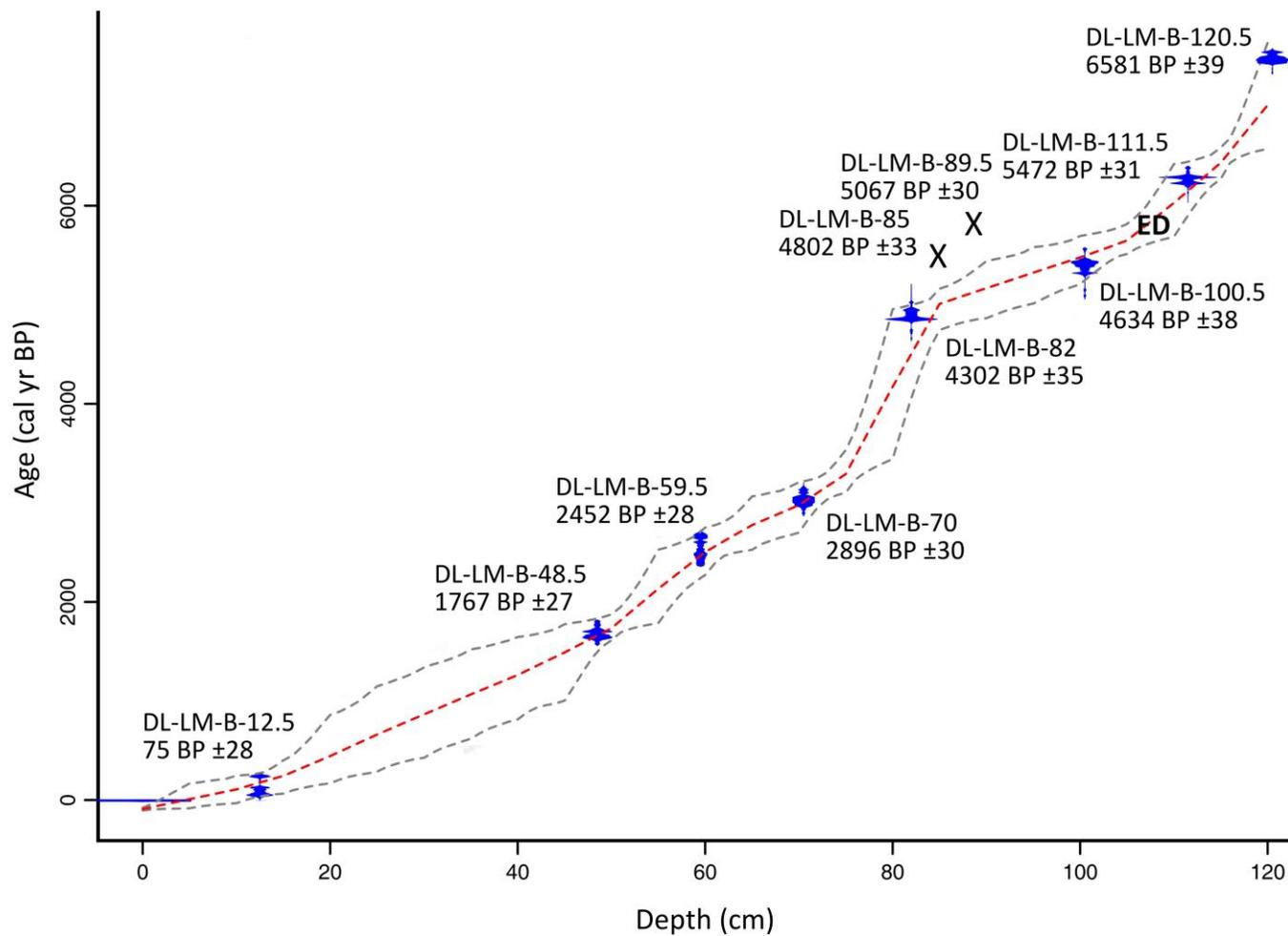


Figure 6.2 - ^{14}C results (uncalibrated) are also shown including the rejected dates at 85 and 89 cm denoted by an X and the Elm Decline (~5800 yr BP; O'Connell and Molloy, 2001) marked as 'ED' on the graph. Blue bands indicate probability distribution for calibrated ^{14}C dates. The red curve follows the 'best' model based on the weighted mean age for each depth, with parallel grey lines indicating the 95% confidence interval.

6.4.3 Chironomid analysis

Chironomid analysis was completed for sixty-seven samples between 120 and 54 cm from core DL-LM-B at 1-cm intervals (sample depths expressed in text using the top depth), in order to target the prehistoric interval in the sediment record. Between 0.25 and 16 cm³ of wet sediment was warmed to 30 °C in a 10% KOH solution and deflocculated for 30 minutes; the sediment was then passed through a 90-µm mesh following standard procedures outlined in Walker (2001). The resulting solution was transferred into a Bogorov plankton counting tray and sorted under a Motic[®] SMZ Series dissection microscope (10 - 40x magnification). For the most part, at least 50 chironomid head capsules (mean = 64) per sample (Quinlan and Smol, 2001) were removed with fine forceps and permanently mounted on slides with Entellan[®]. Low chironomid concentrations were found at 113 cm (46.5 head capsules), 114 cm (28 head capsules) and 116 cm (41.5 head capsules), and these samples were included in statistical analyses. Samples 132, 128 and 124 cm were also sampled for chironomids, but extremely low head capsule concentration (average of 3 head capsules per ml) prevented inclusion in the dataset. A Motic[®] B3 Professional Series compound microscope at 100 - 400x magnification was used for identification of chironomid subfossils. Taxa were identified following Wiederholm (1983), Rieradevall and Brooks (2001), Brooks et al. (2007) and Larocque-Tobler (2014). Chironomid ecology and distribution information were based largely on Brooks et al. (2007), Vallenduuk and Moller Pillot (2007) and Moller Pillot (2009, 2013). A chironomid percentage diagram was constructed using the program C2 version 1.7.6 (Juggins, 2014). Zonation was performed with sum-of-squares partitioning on percentage chironomid data for all taxa, using psimpoll version 4.27 (Bennett 2009-1993).

6.4.4 Geochemical analyses ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N)

Sixty-five samples (119 - 54 cm) were analysed for stable isotope ratios of nitrogen ($\delta^{15}\text{N}$) and carbon ($\delta^{13}\text{C}$) and their elemental content (%N, %C and C:N) by EA-IRMS using a ThermoFinnigan Delta XP interfaced to a Costech ECS 4010 via a ThermoFinnigan MAT Conflo IV at the Isotope Biogeochemistry Laboratory, University of Hawai'i at Mānoa. Sediment samples of 1 cm³ were dried at 100 °C for 24 hours, ground with a mortar and pestle and passed completely through a 200-µm mesh. To remove the influence of carbonates on $\delta^{13}\text{C}$ values, procedures outlined in Harris et al. (2001) were followed; between 2 and 5 mg of homogenized material was weighed into silver capsules and HCl-fumigated. C:N ratios were calculated as the mass ratio of organic carbon to total nitrogen elemental concentrations. Isotope ratios are reported in conventional δ notation relative to atmospheric N₂ and V-PDB for $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$, respectively. Accuracy and precision were 0.2 ‰ or

better relative to reference materials analyzed every 10 samples. For isotopic quantification and correction, reference materials glycine (for N; +11.36 ‰) and acetanilide (for C; -31.32 ‰) were used that are extensively characterized with international certified reference materials including NBS18, NBS19, NIST 1547 for C and NIST3, USGS32, USGS34, USGS35 for N.

6.4.5 Loss-on-ignition

Loss-on-ignition (LOI) analysis was performed on all samples at 1-cm intervals between 120 and 54 cm. Analysis followed standard procedures from Heiri et al. (2001). Sediment samples of 1 cm³ were sequentially ashed at 550 °C and 950 °C to determine organic (LOI₅₅₀) and carbonate (LOI₉₅₀) content of samples. Sand percentage of sediment was analysed every 2 cm from 120 - 54 cm. One cubic centimetre of wet sediment was dried at 100 °C overnight and weighed. The samples were then washed through a 70-µm sieve, remaining organics were removed, and the sand was dried and weighed to derive an estimate of sand percentage by weight. Data was graphed using Sigmaplot version 12.0, including a LOESS smoother (0.2) to show the dominant trends.

6.4.6 Pollen analysis

Sediment samples of 1 cm³ were taken at 2 cm intervals with contiguous sampling carried out from 108 - 104 cm, i.e. the early Neolithic. Standard procedures as implemented in the Palaeoenvironmental Research Unit (PRU), NUIG were used for pollen preparation (see Molloy and O'Connell, 2004). This included the addition of *Lycopodium clavatum* spore tablets, treatment with 10% KOH, 60% HF, and acetolysis. Samples were placed into an ultra-sonicator bath to separate unwanted fine particles, and finally mounted in glycerol. Counting was carried out using a Leica DM LB2 microscope fitted with ×10 oculars at a magnification of ×40. Pollen and spore identification follow Beug (2004, 1961), Fægri and Iversen (1989), Moore et al. (1991), Reille (1995, 1992) and the pollen reference collection in the PRU. Cereal-type pollen were identified following Beug (2004), with a minimum size criterion of 40 µm. Microscopic charcoal fragments (>37 µm) were also counted. More than 1000 total terrestrial pollen (TTP) were counted in each sample (average = 1044 TTP grains).

Pollen percentage diagrams were plotted using the programme CountPol ver. 3.3 by I. Feeser. Taxa excluded from the pollen sum include pollen of aquatic plants, *Sphagnum* spores, algae, non-pollen palynomorphs (NPP) and microscopic charcoal. A percentage composite diagram of distinct ecological groups was also generated, including arboreal, shrubs, ferns, pastoral, arable and

bog. The pollen diagram is zoned into local pollen assemblage zones (PAZ) based on major changes in percentage pollen data.

6.4.7 Statistical analyses

Ordination analyses were performed using Canoco version 5.04 (ter Braak and Šmilauer, 2012) on square-root transformed chironomid percentage data for all common taxa, i.e. taxa present in at least two samples with a relative abundance of $\geq 2\%$ in at least one sample (Quinlan and Smol, 2001). Both principal component analysis (PCA; linear model) and detrended correspondence analysis (DCA; unimodal model) were performed on the chironomid percentage data. A selection was made between linear and unimodal-based ordinations by assessing the gradient length (1.4 standard deviations (SD); linear model recommended) of the species composition along the first two axes (Birks, 1995).

Redundancy analysis (RDA) was used to determine important environmental controls in the chironomid community composition. The statistical significance of eleven environmental variables ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N, *P. lanceolata*, cereal-type pollen, LOI₅₅₀, *Botryococcus*, *Isoetes*, *Pediastrum*, total arboreal pollen, total bog pollen) was assessed using Monte Carlo permutation tests (499 unrestricted permutations) and P-value correction, including the selected false discovery rate, Holm's correction and the Bonferroni correction. Insignificant variables ($p > 0.05$) were dropped from further analysis. The remaining environmental variables were then forward-selected in order of decreasing variance and selection continued as long as each additional variable remained a statistically significant predictor ($p \leq 0.05$) of chironomid assemblage data. Pearson's correlation coefficients, t-tests and eigenvalues ratios (λ_1/λ_2) were used to identify important environmental controls for the chironomid record. Partial RDAs were performed for the forward-selected variables (*Botryococcus*, $\delta^{13}\text{C}$, C:N and *Plantago lanceolata*) to further identify the dominant environmental controls.

Chironomid-inferred mean July air temperature estimates were calculated using a modern calibration set of 50 Irish lakes (Potito et al., 2014) using C2 version 1.7.6 (Juggins, 2014). The classical weighted-averaging inference model for mean July air temperature ($r^2_{\text{jack}} = 0.60$; root mean square error of prediction (RMSEP) = 0.57 °C; Potito et al., 2014) was applied to the chironomid assemblages from L. Meenachrinna. The temperature data was then graphed using Sigmaplot version 12.0, including a LOESS smoother (0.1) to show the dominant trends. Correspondence analysis (CA) and a goodness-of-fit test through canonical correspondence analysis (CCA) were performed using Canoco version 4.54 (ter Braak and Šmilauer, 2006) to assess whether the down-core assemblages from L. Meenachrinna were adequately represented in the Irish training set. A cut-

level of the 10th and 5th percentile in the residual Chi square distances was chosen for the samples with a 'poor' and 'very poor' fit to temperature, respectively (Heiri et al., 2003). The L. Meenachrinna assemblages were passively plotted over the Irish training set data and constrained to July air temperature following Birks (1998) and Heiri et al. (2003).

6.5 Results

6.5.1 Stratigraphy and dating model

The section of the sediment core used for analysis (120 - 54 cm) is composed of dark brown/black lake mud, with sand grains deposited throughout the sediment matrix (i.e. no obvious sand lenses). The analysed sequence for this paper spans 7020 - 2050 cal yr BP, with a temporal resolution of 30 - 180 yr cm⁻¹ (median = 60 yr cm⁻¹). Regarding the chronological precision of the age model, there is a minimum age error of 12.8 years and a maximum age error of 782.5 years (mean age error = 271 years).

6.5.2 Chironomid assemblage zones

Results are presented in the chironomid percentage diagram (Fig. 6.3). A total of 73 taxa were identified with 16 to 31 taxa (mean = 23) per sample.

CAZ 1 ca. 7020 - 5920 cal yr BP (120 - 109.5 cm)

The chironomid community composition is dominated by *Heterotanytarsus* (average of 16%), *Micropsectra insignilobus*-type (13%), *Heterotrissocladius marcidus*-type (11%) and *Stictochironomus rosenschoeldi*-type (8%). Chironomid concentration is very low at 22 chironomid head capsules per ml.

CAZ 2 ca. 5920 - 5220 cal yr BP (109.5 - 92.5 cm)

This zone shows continued presence of *Heterotanytarsus* (average of 13%) and *Heterotrissocladius marcidus*-type (12%). Abundances of *Dicrotendipes nervosus*-type increase to an average of 9%. *Stictochironomus rosenschoeldi*-type abundance declines at 5650 cal yr BP (105 cm; 3%), 5510 - 5480 cal yr BP (101 - 100 cm; ~1%) and are absent at 5360 cal yr BP (96 cm). *Cladotanytarsus mancus*-type abundance peaks from 5730 - 5580 cal yr BP (106 - 103 cm) with a maximum value of 12% at 5730 cal yr BP (106 cm). *Polypedilum nubeculosum*-type abundance also increased during this time to ~8% (5650 - 5620 cal yr BP; 105 - 104 cm).

CAZ 3 ca. 5220 - 4090 cal yr BP (92.5 - 80.5 cm)

The previously dominant *Dicrotendipes nervosus*-type, *Stictochironomus rosenschoeldi*-type and *Micropsectra insignilobus*-type decrease in abundance. *Heterotanytarsus* increases briefly to 32% at 5170 cal yr BP (90 cm), decreasing afterwards to 8% by 4170 cal yr BP (80 cm). *Tanytarsus* undif. (6%), *T. pallidicornis*-type (13%) and *Psectrocladius sordidellus-psilopterus*-type (10%) dominate during this zone. Abundances of *Parakiefferiella bathophila*-type increase in the latter portion of this zone (5040 - 4505 cal yr BP; 86 - 82 cm). Chironomid concentration rises to 241 head capsules per ml.

CAZ 4 ca. 4090 - 2880 cal yr BP (80.5 - 68.5 cm)

Similar to CAZ 1, *Micropsectra insignilobus*-type (average of 13%), *Heterotanytarsus* (12%), *Heterotrissocladius marcidus*-type (10%) and *Stictochironomus rosenschoeldi*-type (8%) dominate CAZ 4. *Micropsectra insignilobus*-type show a large increase in abundance from 3820 - 3170 cal yr BP (78 - 73 cm; ~19%). *Tanytarsus pallidicornis*-type decrease in abundance (7%) during this zone. *Tanytarsus lactescens*-type, *Procladius* and *Synorthocladius* re-enter the record in low abundances.

CAZ 5 ca. 2880 - 2050 cal yr BP (68.5 - 54 cm)

The chironomid composition shows continued dominance by *Heterotanytarsus*, *Heterotrissocladius marcidus*-type and *Micropsectra insignilobus*-type. *Micropsectra insignilobus*-type shows a substantial increase to ~17% from 2430 - 2210 cal yr BP (59 - 56 cm). *Heterotanytarsus* increases from 9 - 17% between 2280 and 2050 cal yr BP (57 - 54 cm), while *Heterotrissocladius marcidus*-type decreases from 7 - 2% during this interval. *Stempellinella/Zavrelia* re-enters the record.

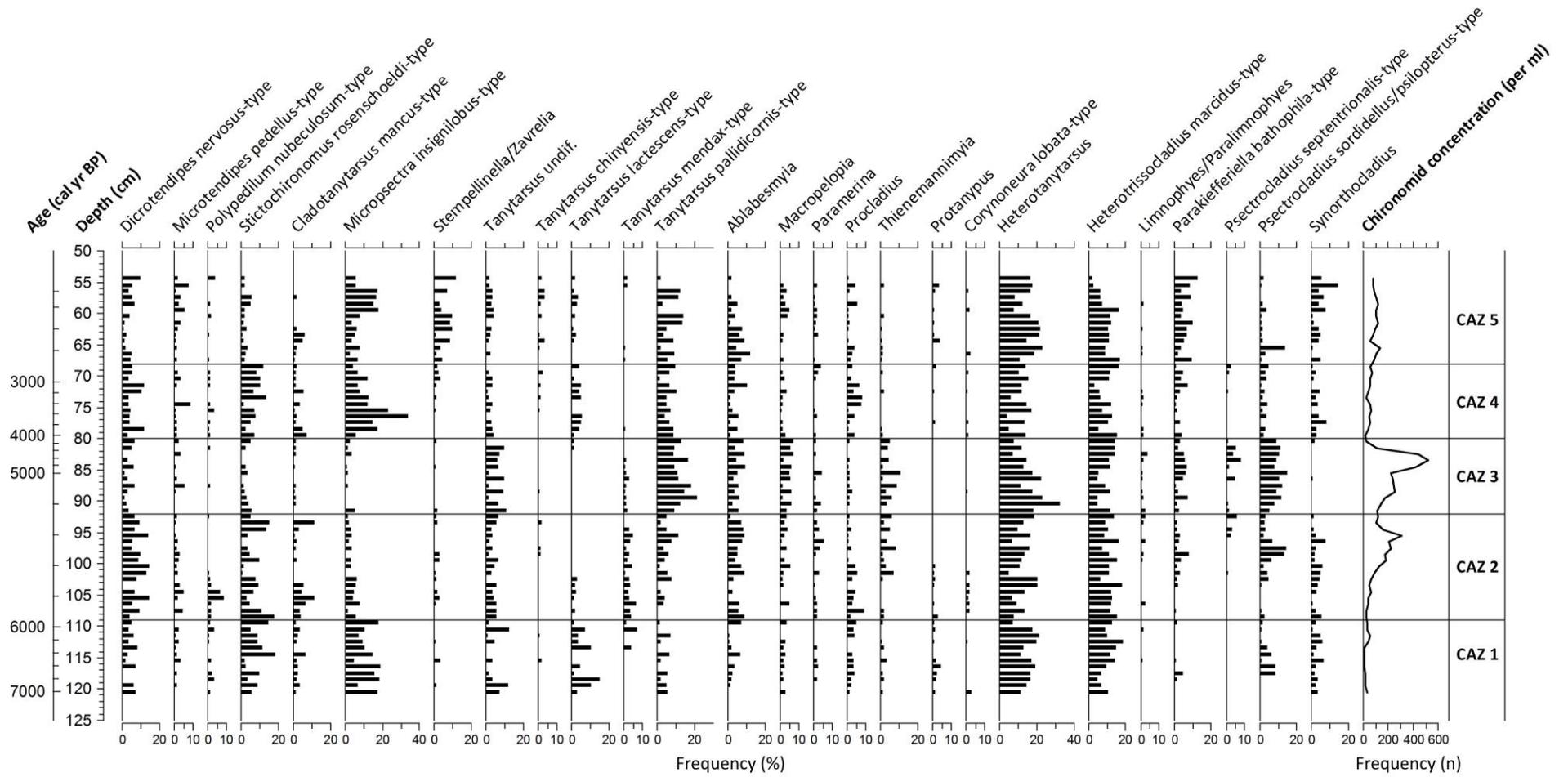


Figure 6.3 - Chironomid percentage diagram from Lough Meenachrinna including chironomid concentration (number of head capsules per ml of sediment).

6.5.3 Pollen

Percentage results are displayed in the pollen profile (Fig. 6.4), with selected pollen curves presented in the composite diagram (Fig. 6.5).

PAZ 1 ca. 8410 - 6670 cal yr BP (132 - 117 cm)

Arboreal pollen (AP) dominates this zone with average representation at ~81%, accounted for by *Corylus* (36 - 17 %) and *Pinus* (21 - 37%) with lesser amounts of *Quercus* and *Ulmus*. *Alnus* registers at 1% at ~7020 cal yr BP (120 cm). Non-arboreal pollen (NAP) is poorly represented with values of ~5%. Algae *Pediastrum* and *Botryococcus* are present throughout, the latter achieving 8% at the top of the zone. Bog pollen representation averages at 9%.

PAZ 2 ca. 6670 - 5840 cal yr BP (117 - 107.5 cm)

AP representation remains high but declines slightly to ~78%, accounted for by the decline in *Pinus* representation to 16% by the end of PAZ 2. *Alnus* continues to expand from the previous zone. *Isoetes* peaks at 22% at 6190 cal yr BP (112 cm). Bog pollen representation average at 13%.

PAZ 3 ca. 5840 - 5510 cal yr BP (107.5 - 101 cm)

This zone is characterised by a decline in AP representation to ~70%. *Ulmus* declines from 14 - 2 % and *Pinus* to ~7%. This coincides with a rise in *Corylus* and *Alnus* representation. The first curve for *P. lanceolata*, a pollen type used primarily as an indicator of pastoral farming in Europe (Behre 1981), is established, and low values of Liguliflorae and *Ranunculus acris*-type are also recorded. An increasing trend in bog pollen representation is recorded in the upper part of the zone *c.f* a rise in *Calluna*. Values of *Isoetes* and *Botryococcus* rise to 14% and 5%, respectively by 5730 cal yr BP (106 cm), with the latter subsequently declining to 3% by the end of the zone. The first peak in microscopic charcoal of 8% is recorded at 5650 cal yr BP (105 cm).

PAZ 4 ca. 5510 - 4340 cal yr BP (101 - 81 cm)

NAP including *P. lanceolata*, Liguliflorae and *Ranunculus acris*-type have a lower representation in this zone. AP falls to 51% by 5230 cal yr BP (92 cm), coinciding with an expansion of bog representation. Subsequently, bog representation decreases as AP increases from 5110 - 4510 cal yr BP (88 - 82 cm). *Botryococcus* remain in low abundances of ~1% during this time.

PAZ 5 ca. 4340 - 2800 cal yr BP (81 - 65 cm)

NAP shows increased representation during PAZ 5. Poaceae increases to ~15% and *P. lanceolata*, Liguliflorae and *Ranunculus acris*-type are recorded in low levels. *Pteridium* increases to ~1%. Cereal-type pollen is recorded for the first time at 3470 cal yr BP (76 cm) and again at 2900 cal yr BP (68 cm). Bog pollen, in particular *Calluna*, Cyperaceae and *Sphagnum* representation, increases during PAZ 5. Overall, AP representation declines to 42% by the end of the zone. Lake taxa *Pediastrum*, *Botryococcus* and *Isoetes* increase between 3820 and 3230 cal yr BP (78 - 74 cm).

PAZ 6 ca. 2800 - 2050 cal yr BP (65 - 54 cm)

AP representation continues to decline from 37% at the beginning of the zone to ~30% above 2610 cal yr BP (62 cm). NAP, including Liguliflorae, *Ranunculus acris*-type and *Rumex acetosa*-type, are present of low frequencies throughout this zone. *P. lanceolata* peaks at 1% by 2360 cal yr BP (58 cm) and cereal-type pollen is more frequent. *Pteridium* representation reaches ~2%. Bog pollen increase to ~42%. *Botryococcus* representation increases to 2% above 2500 cal yr BP (60 cm). *Isoetes* peaks at 15% by 2360 cal yr BP (58 cm). Abundances of microscopic charcoal increase during this time.

Figure 6.4 - Figure caption displayed on the next page

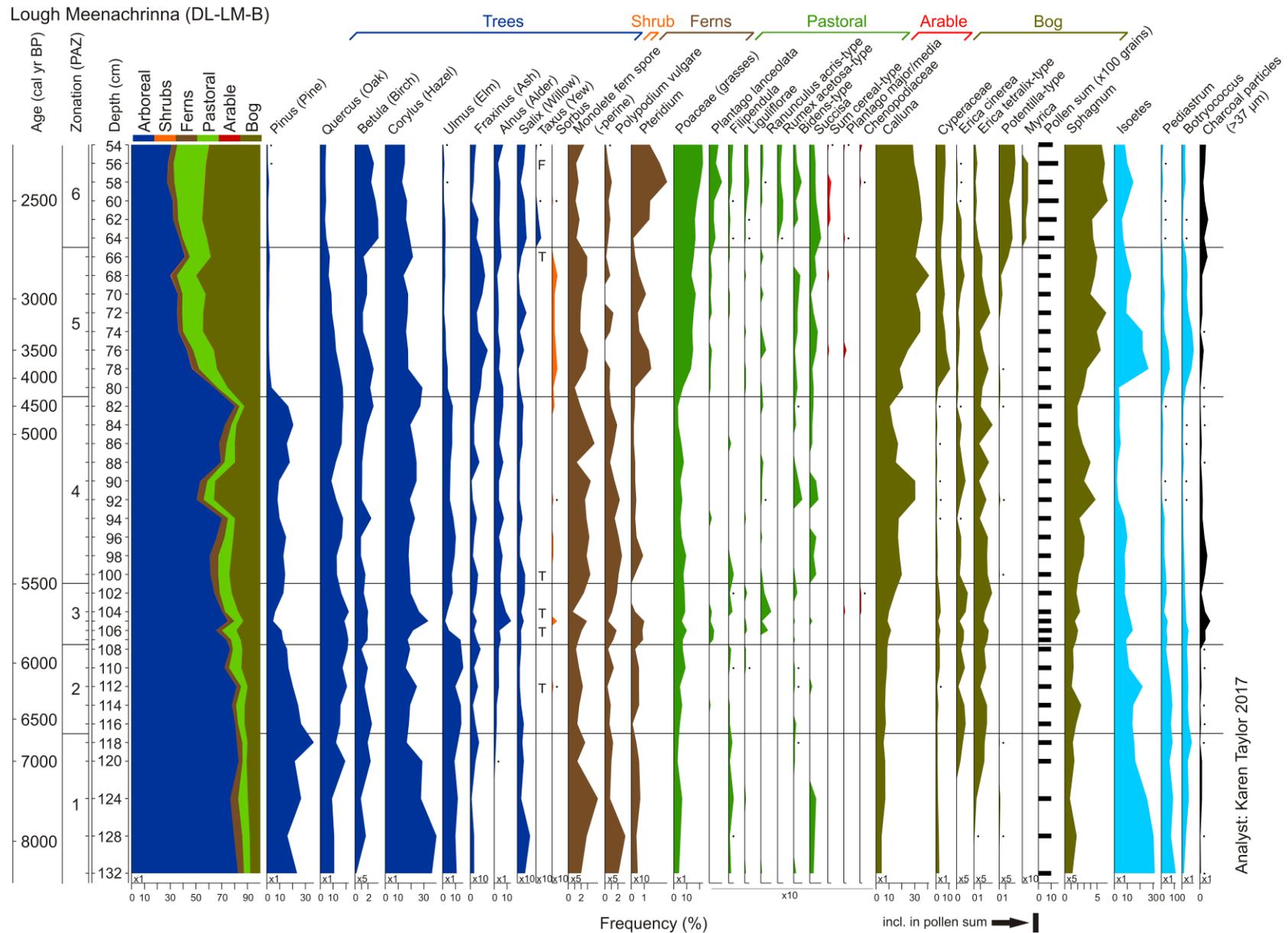


Figure 6.4 - Percentage pollen diagram plotted by depth with secondary axis in calibrated years BP. Ecological groups are differentiated using colour coding. Diagram includes from left to right, a composite percentage pollen diagram and selected pollen percentage curves. Scales are indicated at the base of the individual curves, with normal curves presented at x1 and exaggerated curves at x5 and x10. Dots indicate very low values. The following abbreviations are used for rare occurrences: F = *Fagus* and T = *Tilia*.

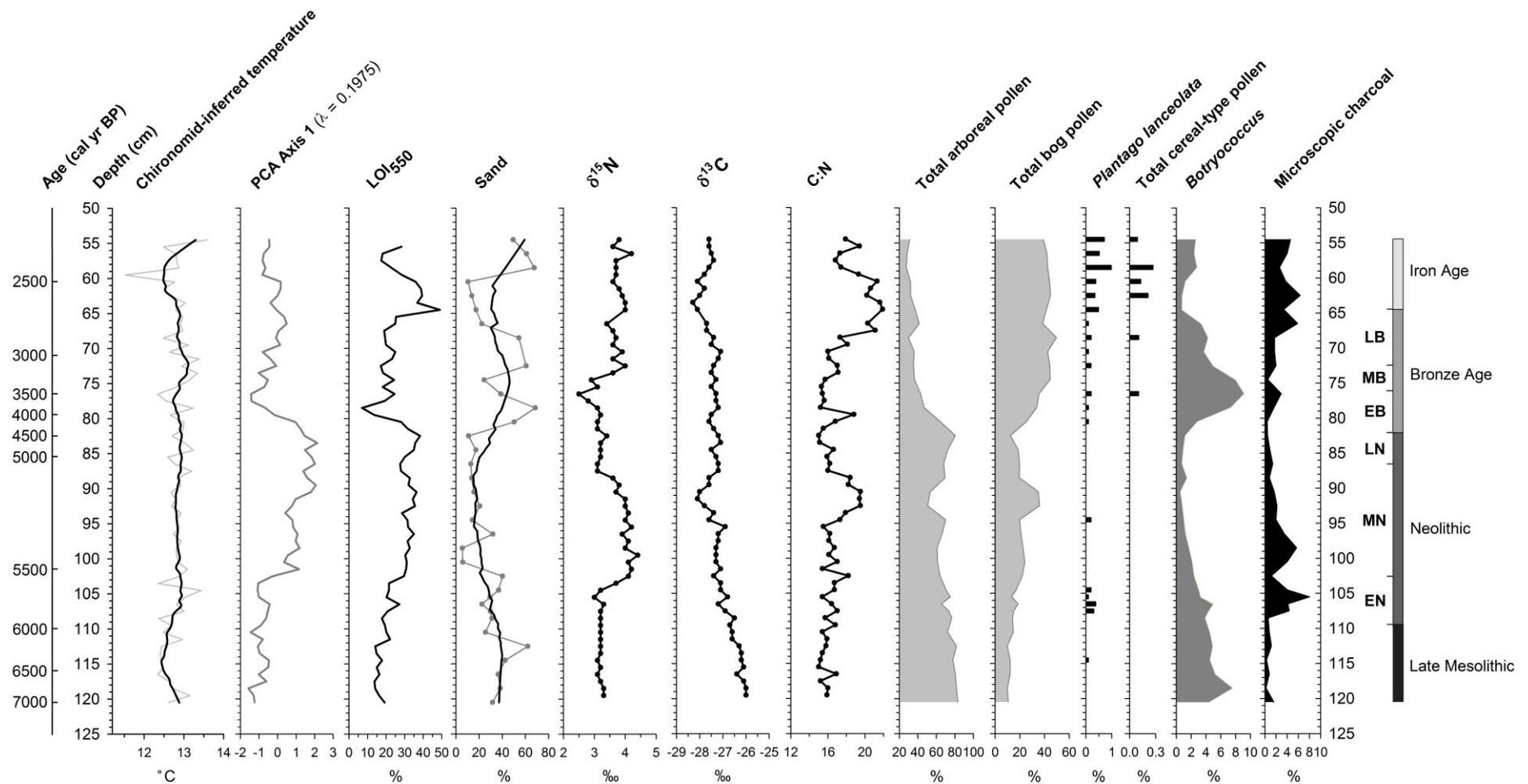


Figure 6.5 - Composite diagram including chironomid-inferred temperature estimation, PCA Axis 1, LOI₅₅₀, sand percentage, geochemical data ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and C:N), selected percentage pollen curves (total arboreal pollen, total bog pollen, *Plantago lanceolata*, total cereal-type pollen and *Botryococcus*) and microscopic charcoal curve from Lough Meenachrinna. Loess smoothers were applied to the temperature (0.1) and sand percentage (0.2) data. Data is plotted by depth (cm) but includes a secondary axis of age (cal yr BP) and a prehistory chronology where: EN = early Neolithic, MN = middle Neolithic, LN = late Neolithic, EB = early Bronze Age, MB = middle Bronze Age and LB = late Bronze Age.

6.5.4 Geochemistry

Geochemistry results are presented in the composite diagram (Fig. 6.5). During the late Mesolithic, $\delta^{15}\text{N}$ values are stable with a mean of +3.2 ‰, $\delta^{13}\text{C}$ shows a slight decreasing trend, while C:N ratios average 15.7. LOI_{550} values are low, averaging 17%, with high sand percentage at ~39% by weight.

In the early Neolithic, $\delta^{15}\text{N}$ averages at +3.2 ‰ from 5950 - 5620 cal yr BP (109 - 104 cm) and increase to +3.7 ‰ by 5550 cal yr BP (102 cm). Stable carbon isotope values and C:N ratios average -26.9 ‰ and 16.4, respectively from 5950 - 5580 cal yr BP (109 - 103 cm). LOI_{550} values increase slightly from 5950 - 5730 cal yr BP (109 - 106 cm), decreasing to 22% by 5580 cal yr BP (103 cm).

During the middle Neolithic, $\delta^{15}\text{N}$ values average +4.1 ‰ between 5510 and 5200 cal yr BP (101 - 91 cm) and decline sharply to +3.1 ‰ by 5070 cal yr BP (87 cm). Stable carbon isotope values average -27.2 ‰ between 5550 and 5320 cal yr BP (102 - 95 cm), declining to -28 ‰ by 5470 cal yr BP (90 cm). C:N ratios are high at ~18.9 from 5200 - 5010 cal yr BP (91 - 88 cm). LOI_{550} remains relatively stable at an average of 32%, with sand percentage showing the lowest values for the profile.

From the late Neolithic to the early Bronze Age, $\delta^{15}\text{N}$ remains stable at approx. +3.2 ‰ from 5040 - 3820 cal yr BP (86 - 78 cm), dropping to +2.5 ‰ at 3470 cal yr BP (76 cm). C:N ratios decrease to ~15.7 from 5040 - 4340 cal yr BP (86 - 81 cm) and incline sharply to 18.8 by 4000 cal yr BP (79 cm). LOI_{550} values decline from 32 - 7% from 4340 - 3820 cal yr BP (81 - 78 cm), while sand percentage shows a substantial increase to 68% at 3820 cal yr BP (78 cm).

During the middle Bronze Age, $\delta^{15}\text{N}$ increases from +3.1 ‰ to +3.6 ‰ from 3290 - 3170 cal yr BP (75 - 73 cm), $\delta^{13}\text{C}$ averages -27.4 ‰ and C:N ratios increase from 15.3 - 17.1. From the late Bronze Age to Iron Age, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ average +3.8 ‰ and -27.7 ‰, respectively. C:N ratios increase to ~21 from 2820 - 2500 cal yr BP (66 - 60 cm) and later decrease to 16.8 by 2280 cal yr BP (57 cm). LOI_{550} values increase to 49% at 2720 cal yr BP (64 cm) with a subsequent decline to 17% by 2280 cal yr BP (57 cm).

6.5.5 Redundancy Analysis (RDA)

The RDA for L. Meenachrinna produced eigenvalues for Axis 1 of 0.1589 and for Axis 2 of 0.0656 (explanatory variables accounted for 28% of the variance in the data), using four statistically significant forward-selected variables (*Botryococcus*, $\delta^{13}\text{C}$, C:N and *P. lanceolata*) (Fig. 6.6a and Table 6.2). The aquatic plant *Botryococcus* showed the strongest relationship to the RDA Axis 1, followed by $\delta^{13}\text{C}$. The RDA samples bi-plot highlights a general shift in the chironomid community composition in CAZ 4 back to the right of the biplot (Fig. 6.6a), largely driven by an increase in oligotrophic taxa

Heterotanytarsus, *Micropsectra insignilobus*-type, *Heterotrissocladius marcidus*-type and *Stictochironomus rosenschoeldi*-type (Fig. 6.6b). A similar shift is exhibited in PCA Axis 1 values during this time (Fig. 6.5).

Partial RDAs indicated that *Botryococcus* accounts for a significant proportion of the variance in the chironomid community, explaining 12.9% of the variance on its own and 8.4% with other variables partialled out (Table 6.3). $\delta^{13}\text{C}$, C:N ratios and *P. lanceolata* strengthened as predictors when effects of other variables were partialled out.

Figure 6.6a - Figure caption displayed on the next page

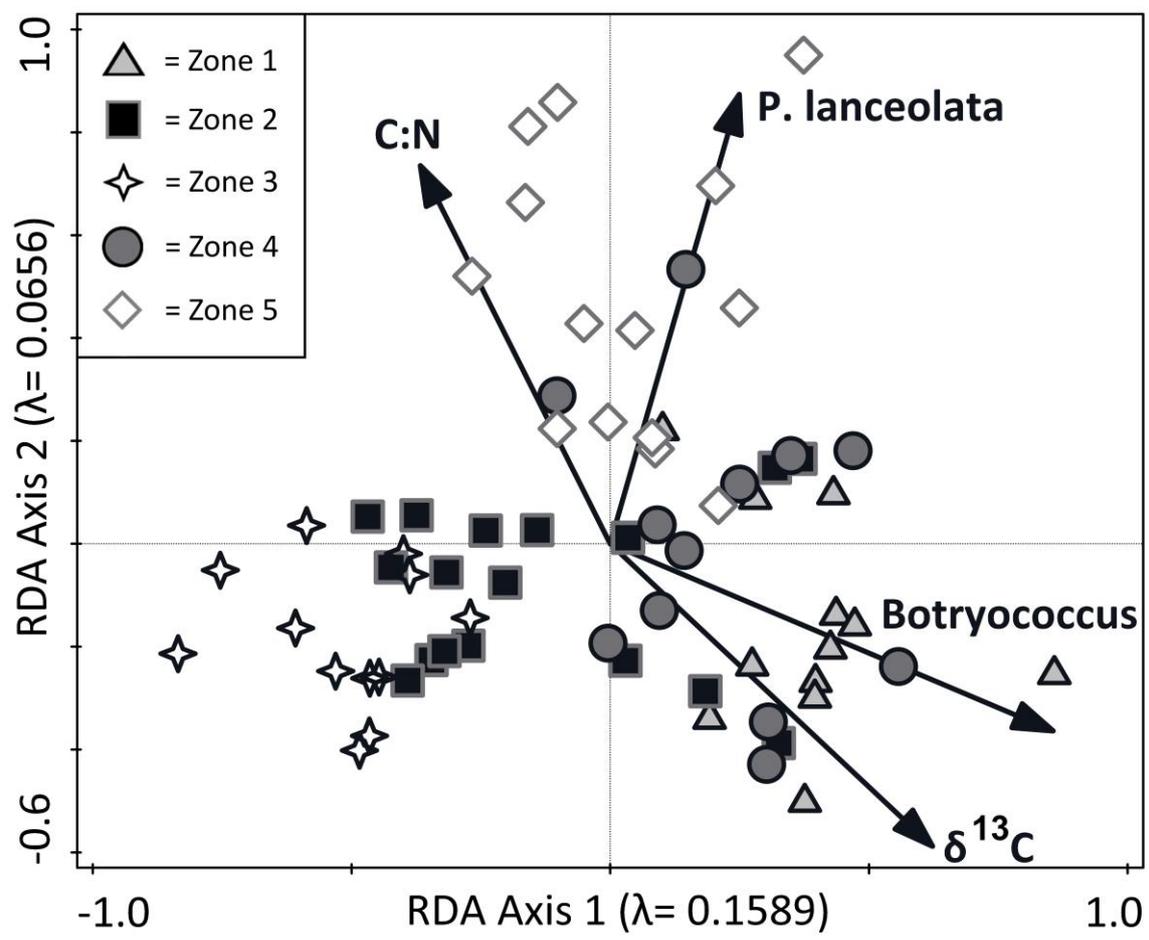


Table 6.2 - Summary and performance statistics for significant environmental variables relating to the chironomid distributions at Lough Meenachrinna.

	Lough Meenachrinna			
	Axis 1	Axis 2	Axis 3	Axis 4
<i>PCA - Full Model</i>				
Eigenvalue	0.198	0.093	0.070	0.062
Cum % var. spp.	19.8	29.0	36.0	42.2
<i>RDA - Full Model</i>				
Eigenvalue	0.159	0.066	0.035	0.021
Pseudo-canonical corr.	0.896	0.812	0.871	0.602
Cum % var. spp.	15.9	22.4	25.9	28.0
<i>T-values</i>				
Botryococcus	6.98*	-0.82	0.09	1.15
$\delta^{13}\text{C}$	3.92*	-3.64*	-2.58*	-0.90
C:N	-1.41	4.96*	-1.35	0.26
<i>P. lanceolata</i>	1.17	5.87*	2.13*	-0.58

*p < 0.05

Table 6.3 - Partial RDAs of four common environmental variables (*Botryococcus*, $\delta^{13}\text{C}$, C:N and *Plantago lanceolata*) by themselves and with the effects of other environmental variables partialled out for each lake.

Variable	Covariable		Lough Meenachrinna
<i>Botryococcus</i>	None	λ_1	0.129
		λ_1/λ_2	0.971
		% variance	12.9*
	$\delta^{13}\text{C}$, C:N, <i>P. lanceolata</i>	λ_1	0.066
		λ_1/λ_2	0.670
		% variance	8.4*
$\delta^{13}\text{C}$	None	λ_1	0.057
		λ_1/λ_2	0.324
		% variance	5.7*
	C:N, <i>P. lanceolata</i> , <i>Botryococcus</i>	λ_1	0.051
		λ_1/λ_2	0.511
		% variance	6.6*
C:N	None	λ_1	0.035
		λ_1/λ_2	0.176
		% variance	3.5*
	<i>P. lanceolata</i> , <i>Botryococcus</i> , $\delta^{13}\text{C}$	λ_1	0.044
		λ_1/λ_2	0.445
		% variance	5.8*
<i>P. lanceolata</i>	None	λ_1	0.063
		λ_1/λ_2	0.314
		% variance	6.3*
	<i>Botryococcus</i> , $\delta^{13}\text{C}$, C:N	λ_1	0.065
		λ_1/λ_2	0.653
		% variance	8.2*

*p < 0.05

6.5.6 Chironomid-inferred temperature

The chironomid-inferred temperature model (Potito et al., 2014) produced mean July air temperature estimates ranging from 11.5 - 13.6 °C (Fig. 6.7). There were 55 common chironomid taxa between the L. Meenachrinna chironomid assemblage and the Irish training set. Six chironomid taxa were not present in the training set - *Stictochironomus rosenschoeldi*-type, *Micropsectra* undif., *Tanytarsus* undif., *Macropelopia*, *Nanocladius rectinervis*-type and *Psectrocladius calcaratus*-type, and were thus excluded from the temperature model. The absence of *Stictochironomus rosenschoeldi*-type, a dominant taxon in the assemblage, may compromise the accuracy of the model for this site.

Chironomid-inferred temperatures (C-IT) drop 0.7 °C, from 13.1 °C at 6900 cal yr BP (119 cm) to ~12.4 °C between 6550 and 6190 cal yr BP (116 - 112 cm) (Fig. 6.5 and 6.7). C-IT increases briefly to 13 °C at 6110 cal yr BP (111 cm), declining afterwards. During the early Neolithic temperatures increase from 12.4 - 13 °C by 5800 cal yr BP (107 cm), averaging 13.1 °C from 5800 - 5620 cal yr BP (107 - 104 cm), after which it drops from 13.4 - 12.4 °C between 5620 and 5580 cal yr BP (104 - 103 cm). C-ITs are relatively stable for the mid to late Neolithic at ~12.9 °C (5550 - 4670 cal yr BP; 102 - 83 cm). In the early Bronze Age, C-IT declines from 13.2 - 12.3 °C between 3820 and 3470 cal yr BP (78 - 76 cm). This is followed by an increase to 13.2 °C from 3230 - 3170 cal yr BP (74 - 73 cm). Lastly, during the Iron Age there is a substantial drop of 1.3 °C from 12.8 - 11.5 °C from 2500 - 2430 cal yr BP (60 - 59 cm), followed by a general increasing trend from 12.9 - 13.6 °C from 2360 - 2050 cal yr BP (58 - 54 cm).

The CA indicates that the downcore assemblages from L. Meenachrinna were adequately represented in the Irish training set model, with the L. Meenachrinna chironomid assemblages associated with high elevation lakes from Potito et al. (2014) (Fig. 6.7). The goodness-of-fit test (CCA) flagged samples 76, 118 and 113 cm as a 'very poor fit' (5th percentile in the modern residual Chi square distances) and samples 57, 73, 116 and 120 cm as a 'poor fit' (10th percentile in the modern residual Chi square distances). July mean air temperature for 2017 was calculated using data from the local weather station in Ballyshannon, Co. Donegal (Met Éireann, 2017c) and a global lapse rate of 6.5 °C/km (Lutgens and Tarbuck, 1995) (Fig. 6.7).

Figure 6.7 - Figure caption displayed on the next page

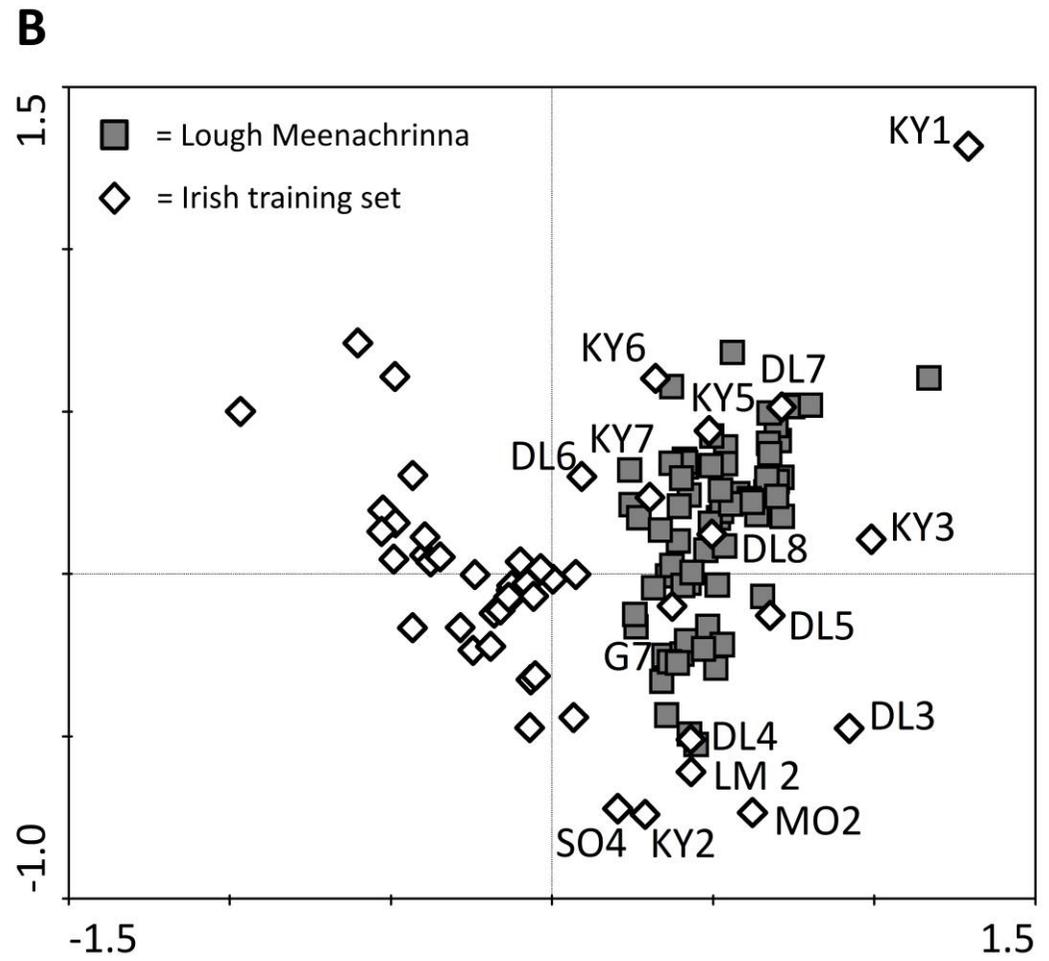
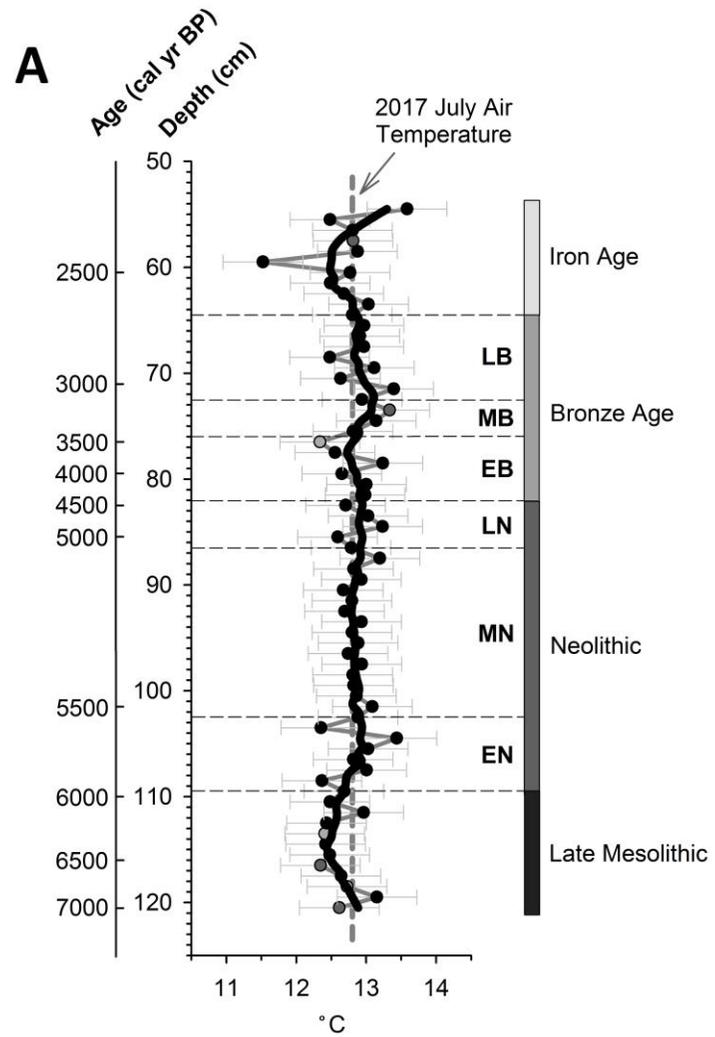


Figure 6.7 - A) Chironomid-inferred mean July air temperature reconstruction for Lough Meenachrinna, County Donegal spanning 7020 - 2050 cal yr BP, including a 2017 mean July temperature estimation. The solid black lines represent a LOESS smoother (0.1). The circular symbols represent goodness-of-fit (CCA) with the 50-lake Irish training set (Potito et al., 2014) - black (good fit), dark grey (poor fit - 10th percentile) and light grey (very poor fit - 5th percentile). Data is plotted by depth (cm) but includes a secondary axis of age (cal yr BP) and a prehistory chronology (for conventions see Fig. 5 caption). B) A correspondence analysis (CA) with the L. Meenachrinna assemblages passively plotted over the Irish training set data from Potito et al. (2014) and constrained to July air temperature. Associated lakes from the Potito et al. (2014) study are labelled.

6.6 Discussion

The palaeoenvironmental results suggest that L. Meenachrinna was an oligotrophic lake for the majority of the mid to late Holocene (7020 - 2050 cal yr BP) based on the chironomid, pollen and geochemical data. The pollen record shows minimal pastoral indicators in the early Neolithic, with increased evidence for pastoral and arable farming during the Bronze Age, and in particular the Iron Age. As L. Meenachrinna is a small basin in an upland region (northwest facing) and given the prevailing winds and proximity to the coast, the pollen profile likely reflects a local signal. Previous studies from northwest Ireland have shown that pastoral farming activity can exhibit a strong control over diversity and abundance of chironomid communities during the prehistoric period, with chironomid compositional change roughly proportional to the scale of Neolithic and Bronze Age farming activity (Taylor et al., 2017a, 2017b, 2013). However, human activity does not appear to be a driving force in lake system change at L. Meenachrinna, as peaks in farming indicators (e.g. non-arboreal pollen indicative of grassland/pasture and increased $\delta^{15}\text{N}$ values - indicative of changes in nitrogen cycling with early land management), were not concurrent with major fluctuations in the chironomid assemblages.

6.6.1 Ecological Reconstruction

Late Mesolithic

The chironomid assemblage during the late Mesolithic (7020 - 5950 cal yr BP) reflects a cold, oligotrophic lake system with the dominance of *Heterotanytarsus*, *Heterotrissocladius marcidus*-type, *Micropsectra insignilobus*-type and *Stictochironomus rosenschoeldi*-type (Brooks et al., 2007; Moller Pillot, 2013, 2009). The presence of *Botryococcus* (a green planktonic microalga) in the pollen profile also infers an oligotrophic lake system, as *Botryococcus braunii* is found in abundance in 'dystrophic' acidic brown water lakes and is most commonly recorded in shallow, partly saline lake systems (Tyson, 2012; Warren, 1986). RDA verifies an association of *Botryococcus* with the chironomid assemblage from 7020 - 5950 cal yr BP (CAZ 1).

High percentages of arboreal pollen reflect a densely forested landscape dominated by pine, hazel, oak and elm during the late Mesolithic, with the expansion of alder from 7020 cal yr BP representing the Boreal/Atlantic Transition, though somewhat later than elsewhere (see Molloy and O'Connell, 2004). Fossit et al. (1994) shows the expansion of *Alnus* between 8040 and 7500 cal yr BP (recalibrated) from the Loughros Peninsula (15 km northeast of L. Meenachrinna) and the Rosses, Co. Donegal (38 km northeast of the study site).

The geochemical results corroborate the chironomid and pollen data from the late Mesolithic, revealing an unproductive oligotrophic system. Nitrogen stable isotope values remain low, and relatively high C:N ratios reflect a prominent allochthonous source for lake sediment organic matter (Botrel et al., 2014; Cohen, 2003; Meyers and Teranes, 2001; Woodward et al., 2012). The decreasing $\delta^{13}\text{C}$ values during the late Mesolithic are possibly associated with the declining *Botryococcus* representation, as cultured bulk *B. braunii* has a $\delta^{13}\text{C}$ value of -16.9‰ (Huang et al., 1999), and *Botryococcus* and $\delta^{13}\text{C}$ exhibit positive correlation (Pearson's correlation coefficient (r) = 0.559; $p < 0.01$) through the lake record. C:N ratios show a negative correlation with *Botryococcus* (Pearson's correlation coefficient (r) = -0.536*; $p < 0.01$), which is typical of lake algae. RDA reveals an association between high $\delta^{13}\text{C}$ values and the chironomid assemblage from 7020 - 5950 cal yr BP (CAZ 1), highlighting within-lake processes as a controlling factor on chironomid compositional change.

Early Neolithic

Despite the study site's remote location, the classic mid-Holocene Elm Decline recognised in pollen diagrams from all over Ireland is recorded in L. Meenachrinna at 5730 cal yr BP. This compares well with pollen profiles from elsewhere (Fossitt, 1994; O'Connell and Molloy, 2001; Parker et al., 2002; Stolze et al., 2013; Whitehouse et al., 2014). The NAP record including *P. lanceolata* and microscopic charcoal reflects a low level of human activity around L. Meenachrinna in the early Neolithic. However, AP remains high and there is no evidence of a major Landnam event during this time.

L. Meenachrinna remains oligotrophic during the early Neolithic, inferred by the presence of *Heterotanytarsus* and *Heterotrissocladius marcidus*-type in the chironomid assemblage, with relatively high C:N ratios reflecting continued low productivity within the lake system (Cohen, 2003; Meyers and Teranes, 2001). The increased abundance of *Cladotanytarsus mancus*-type and *Polypedilum nubeculosum*-type possibly infer a change in climate to warmer temperatures (Brooks et al., 2007; Moller Pillot, 2009). Increases in these taxa could also be a result of increased farming activity. However, this is unlikely given the low levels of $\delta^{15}\text{N}$ recorded here, in comparison to lakes situated in the centre of a landscape rich in Neolithic monuments in Co. Sligo (Taylor et al., 2017a). At these sites NAP is also high, with *P. Lanceolata* attaining 6 - 9 % versus 1% of L. Meenachrinna. In addition, low *Pediastrum* and *Isoetes* representation and LOI_{50} indicates a stable catchment with little to no human impact during this time.

Middle Neolithic

Anthropogenic activity is not recorded in the catchment during the middle Neolithic (see NAP <8%). AP representation remains high but declines starting at 5230 cal yr BP, concomitant with a local expansion of bogland. The chironomid assemblage reflects the expansion of bog in the catchment area with increased abundance of *Heterotanytarsus*, which is associated with oligohumic lakes (brown water) (Moller Pillot, 2013). The decline to more negative $\delta^{13}\text{C}$ values may reflect the expansion of bogland, as the bulk $\delta^{13}\text{C}$ value of *Sphagnum* is -27.5‰ (Meyers and Teranes, 2001); while C:N ratios indicate increased allochthonous inputs during this time (Cohen, 2003).

The PCA axis 1 highlights a general change in the chironomid composition during the middle to late Neolithic (5230 - 4170 cal yr BP), with increases in abundance of chironomid taxa associated with more temperate conditions. *Tanytarsus pallidicornis*-type, associated with warmer water in the Irish training set (Potito et al., 2014), and *Psectrocladius sordidellus/psilopterus*-type (associated with temperate, humic sandy bottomed lakes; *psilopterus*-type are also acidophilic (Moller Pillot, 2013)) become dominant, while *Stictochironomus rosenschoeldi*-type decreases in abundance. Redundancy analysis shows a negative relationship between cold, oligotrophic taxa *Micropsectra insignilobus*-type and *Stictochironomus rosenschoeldi*-type with *Tanytarsus pallidicornis*-type and *Psectrocladius sordidellus/psilopterus*-type. The expansion of woodland (particularly pine) concurrent with a decrease in bog pollen and from 5110 - 4510 cal yr BP may reflect a drier climate, which facilitated the expansion of pine on bog (O'Connell and Molloy, 2001). C:N ratios reflect an increase in lake productivity and/or decreased input of terrestrial material from 5070 - 4170 cal yr BP. The increased LOI₅₅₀ and low sand percentage reflects a higher content of organic matter in the lake sediment.

Bronze Age

A possible inwash event is reflected in the LOI₅₅₀ and pollen data at 3820 cal yr BP. LOI₅₅₀ values show a sudden drop coinciding with a substantial increase in sand percentage, inferring an inwash of inorganic material. Lake taxa in the pollen profile also reflect erosion/sediment inwash with a large increase in *Isoetes* at 3820 cal yr BP (Vuorela, 1980). The *Botryococcus* bloom from 3820 - 3230 cal yr BP could infer a decrease in productivity considering the large increase in abundance of the cold, oligotrophic taxon *Micropsectra insignilobus*-type from 3820 - 3170 cal yr BP, and a decrease in C-IT from 3820 - 3470 cal yr BP (see below). Lower C:N ratios also reflect more autochthonous productivity during this time. Organic input from the expansion of bog appears to offset the less negative $\delta^{13}\text{C}$ signal expected from the presence of the large bloom of *Botryococcus* (Huang et al., 1999; Meyers and Teranes, 2001).

PCA Axis 1 shows a shift in the chironomid assemblage during the Bronze Age (4170 - 2900 cal yr BP) back to a composition similar to that of the Late Mesolithic. Cold, oligotrophic taxa *Micropsectra insignilobus*-type, *Stictochironomus rosenschoeldi*-type, *Heterotanytarsus* and *Heterotrissocladius marcidus*-type dominate the stratigraphy once again (Brooks et al., 2007; Moller Pillot, 2009; Vallenduuk and Moller Pillot, 2007). The pollen record highlights an expansion of bogland from 4170 cal yr BP concurrent with the disappearance of pine in the landscape. The increased abundance of Poaceae and Cyperaceae most likely reflect the growth of grasses and sedges on the bog surface. Anthropogenic indicators Liguliflorae, *P. lanceolata* and *Ranunculus acris*-type are recorded at low levels and cereal-type pollen are first recorded at 3470 cal yr BP. These suggest farming (pastoral and arable) within the catchment, albeit at very low levels. A lack of concurrent increases in $\delta^{15}\text{N}$ and similar chironomid assemblages to the late Mesolithic, as exhibited in the RDA sample bi-plot (Fig. 6.6a) suggest that farming activity had little to no impact on L. Meenachrinna during the Bronze Age.

Iron Age

The chironomid assemblage at the end of late Bronze Age into the Iron Age continues to show an oligotrophic lake system. The pollen record reflects an increase in farming activity (pastoral and arable) during the Iron Age (see expansion in a suite of NAP taxa and cereal-type pollen). However, L. Meenachrinna remains relatively un-impacted by farming activity with the predominance of *Heterotanytarsus*, *Heterotrissocladius marcidus*-type and *Micropsectra insignilobus*-type. The high C:N values also indicate low lake productivity from 2820 - 2500 cal yr BP.

6.6.2 Temperature

This study provides a unique independent record of past temperature change in Ireland for the mid to late Holocene. The multi-proxy approach allowed for separation of climate and any potential human influence using geochemical and pollen analysis. The chironomid-inferred temperature (C-IT) model from L. Meenachrinna produced a narrow temperature range of ~ 2.1 °C for the time frame under investigation (7020 - 2050 cal yr BP). This is to be expected given Ireland's location and maritime climate. Global Holocene temperatures are relatively subdued with summer temperatures during the Holocene Thermal Maximum (7000 - 5000 yr BP) only rising by 0.5 - 1.5 °C above the preindustrial level in the mid- and high latitudes of Europe (Renssen et al., 2012).

During the late Mesolithic, C-IT shows a drop of 0.7 °C from 6550 - 6190 cal yr BP, highlighting a shift to colder conditions for ~ 360 years. This coincides with a cold phase in the Swiss

Alps from 6600 - 6200 cal yr BP, inferred through pollen and macrofossil analysis (Haas et al., 1998). By the end of the late Mesolithic, a brief increase in C-IT occurs at 6110 cal yr BP. This warm event coincides with several peatland and dendrochronological studies in Ireland and England noting a shift to drier conditions during this time (Hughes et al., 2000; Langdon et al., 2003, 2012; Turney et al., 2006). There is a considerable increase in C-IT of 0.7 °C from 5800 - 5620 cal yr BP during the early Neolithic period. This warming phase of ~180 years corresponds with several peatland studies in Scotland (Anderson, 1998) and Ireland (Caseldine et al., 2005), showing a period of drier climatic conditions and/or decreased peat accumulation rates. A tree-ring chronology of Irish bog oaks also reflects warm/dry conditions from 5850 - 5400 cal yr BP (Briffa and Atkinson, 1997). Stolze et al. (2013) provide a high-resolution pollen and geochemical record from Templevanny Lough in northwest Ireland, inferring a period of ameliorated climatic conditions (increasing spring/summer temperatures and declining precipitation) from 5860 - 5620 cal yr BP. During the early Neolithic, a drop of 1 °C in C-IT occurs at 5580 cal yr BP. Magny and Haas (2004) report higher lake-levels between 5550 and 5300 cal yr BP with a strong cooling episode at 5550 cal yr BP, which coincide with glacier advancement and tree-limit decline in the Swiss Alps. Stolze et al. (2013) note a shift to wetter conditions at 5620 cal yr BP in the pollen and geochemical record in Templevanny Lough, coinciding with an increase in bog surface wetness at Derragh Bog in the Irish midlands (Langdon et al., 2012).

C-IT from L. Meenachrinna remains relatively stable at ~12.9 °C for the majority of the middle to late Neolithic period (5545 - 4670 cal yr BP). By the early Bronze Age, C-IT briefly decline to 12.3°C at 3470 cal yr BP. A deterioration in climate is also reported in the Alpine timberline reconstruction in Haas et al. (1998), with a cold phase from 3500 - 3200 cal yr BP. Similarly, Barber et al. (2004) note a cold/wet event at 3500 cal yr BP. This cold event at L. Meenachrinna is followed by a warming from 3230 - 3170 cal yr BP, corresponding with a dry phase (3200 - 2750 cal yr BP) identified in a review of multiple Irish palaeoclimate reconstructions from peatlands, lakes and a speleothem (Swindles et al., 2013).

The last notable fluctuation in the C-IT occurs during the early Iron Age, with a substantial drop of 1.3 °C at 2430 cal yr BP. The decline in C-IT coincides with a wet event in the Irish peatland record from 2670 - 2430 cal yr BP in Langdon et al. (2012), a cold phase from 2600 - 2350 cal yr BP in Haas et al. (1998) and a cold/wet phase in Irish records from 2700 - 2400 cal yr BP (Swindles et al., 2013). A general increasing trend occurs into the Iron Age from 2355 cal yr BP at L. Meenachrinna. This trend is identified in Irish peat records (Swindles et al., 2013) with a dry phase from 2250 - 1550 cal yr BP (Swindles et al., 2013) and from 2120 - 1660 cal yr BP (Langdon et al., 2012).

Lough Meenachrinna successfully provides an independent C-IT record for the Irish prehistoric period. The record should be interpreted with a degree of caution as C-IT estimations from a single study site may not always provide a reliable regional Holocene temperature signal due to subdued temperature variation and sample-specific errors (Velle et al., 2005). However, agreement with broad trends from other Irish and regional records shows that C-ITs generally reflect past environmental conditions. It is a challenge to find lakes with little to no human impact through the Irish Neolithic and Bronze Age, and high elevation lakes with associated low sedimentation rates seem to be the best option in the study region. Our suggestion for future investigations of mid to late Holocene temperature change is to include multiple high elevation study sites, using a multi-proxy approach to assess land-use change and human impacts, in order to create a composite C-IT estimation for Ireland.

6.7 Conclusions

This study provides the first mid to late Holocene chironomid-inferred temperature model for Ireland, creating a valuable climatic context for the development of Irish society during the Neolithic and Bronze Age. This reconstruction provides evidence of multiple fluctuations in temperature during the mid to late Holocene including a cold phase during the late Mesolithic (6550 - 6190 cal yr BP), and a warming phase in the early Neolithic period (5800 - 5620 cal yr BP). C-IT reflect a relatively stable climate during the middle to late Neolithic, followed by a cold event at 3470 cal yr BP, a later warm phase at 3230 cal yr BP and a brief decline in temperatures at 2430 cal yr BP during the Iron Age. The untangling of temperature change from human impact in the prehistoric chironomid record is a challenge. The inclusion of chironomid subfossils, pollen analysis and geochemistry in a multi-proxy approach has been demonstrated here to be an effective way to address this problem, and is recommended as a methodological approach in future climatic reconstruction in Ireland.

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Chapter 7 - Discussion and conclusions

This concluding chapter will integrate the main findings from the three research papers, highlighting the key contributions of this research project.

7.1 General findings

The multi-proxy methodological approach used of chironomid subfossils, lake sediment geochemistry ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N) and pollen analyses was highly successful and verifies that palaeolimnological indicators can elucidate the environmental impacts of prehistoric farming, answering the first research question. Using general ecological interpretations of biotic and geochemical proxies with multi-variant statistical analyses, palaeolimnological data indicated that prehistoric farming was extensive during the Neolithic and Bronze Age in County Sligo. Close linkages between human land-use and lake conditions were revealed at Templevanny Lough and Cooney Lough, with periods of farming activity regularly causing lake eutrophication.

Pollen and lake sediment geochemistry were used to indicate the presence of prehistoric farming in the catchment area, as represented by increases in non-arboreal pollen indicative of grassland/pasture (NAPp/PPI), cereal-type pollen and increased $\delta^{15}\text{N}$. Lake sediment geochemistry indicated nutrient input at each site, as reflected by high values of $\delta^{15}\text{N}$ often in concert with a high NAPp/PPI representation. Nitrogen likely entered the lake system through direct inputs of ^{15}N -enriched animal waste (Woodward et al., 2012; Botrel et al., 2014) and/or increased soil erosion (Kendall, 1998; Talbot, 2001). As lakes are nitrogen (and phosphorous) limited systems, nutrient input from farming quickly leads to increased lake productivity, i.e. cultural eutrophication. The chironomid and stable isotope data provide evidence for cultural eutrophication at Lough Dargan, Templevanny Lough and Cooney Lough. Resulting changes in trophic status were identified through increased abundances of eutrophic chironomid taxa, higher $\delta^{15}\text{N}$ values and in some instances lower C:N ratios, reflecting more autochthonous productivity. In chapter 5, redundancy analysis (RDA) and partial RDAs were used to further verify these results. $\delta^{15}\text{N}$ and NAPp were established as important controlling factors of chironomid community compositional change during the Neolithic and Bronze Age at the three human impacted sites.

7.2 Inferences from agriculturally active catchments

The palaeoenvironmental data generated from this research provides evidence for the presence, timing, magnitude and location of farming activity in County Sligo, for use in archaeological inquiry. Pollen records revealed a predominance of pastoral farming at all Neolithic sites, with arable farming

(indicated by cereal-type pollen) becoming more prevalent during the Bronze Age. Whitehouse et al. (2014) suggests that arable farming during the Neolithic period in Ireland likely consisted of small, intensive permanent plots. Cereals also have a naturally low pollen distribution which would explain the lack of consistent evidence through the record, and pollen quantities can also be influenced by depositional pathways, i.e. affected by inwash/precipitation events (Moore et al., 1991).

Prehistoric farming clearly impacted the freshwater lake systems investigated in this project. However, it can be difficult to assess whether the high levels of $\delta^{15}\text{N}$ found at the human impacted sites were associated with manure runoff from pastoral farming or from fertilization of crops in the catchment area. It has been suggested that manuring of arable plots did take place to maintain fertility (Bogaard et al., 2007; Fraser et al., 2011). However, high $\delta^{15}\text{N}$ values were found in concert with increases in NAPp/PPI at each site in this project. Therefore, high $\delta^{15}\text{N}$ values from the human impacted lakes are likely indicative of animal husbandry (Cohen, 2003; Taylor et al., 2013; Woodward et al., 2012) or from increased soil erosion. Grazing of domesticated animals likely took place adjacent to the lakesides of the three study lakes to avail of the natural water resource. This was a common historic farming practice until modern environmental laws were implemented. Consequently, nitrogen entered the lake systems either directly through runoff of animal waste or indirectly through soil erosion. Partial RDAs, discussed in chapter 5, further verify that $\delta^{15}\text{N}$ and NAPp/PPI were responsible for a significant proportion of the variance in the chironomid communities of the human impacted sites. $\delta^{13}\text{C}$ and C:N were also identified as common controls, reflecting the importance of lake productivity and increased erosion. Geochemical data from the control site revealed an equally large increase in $\delta^{15}\text{N}$ during the Neolithic period. However, this increase in $\delta^{15}\text{N}$ values was not concurrent with NAPp or any large changes in the chironomid community as seen at the impacted sites. The increase in $\delta^{15}\text{N}$ values at Lough Meenachrinna is likely a result of natural within-lake processes and not from nutrient input from farming activity in the catchment.

Chironomid communities were found to be sufficiently sensitive to scale/intensity of prehistoric farming at the human impacted sites, to answer the second research question. The chironomid assemblage data was found to be roughly proportional to the scale of Neolithic and Bronze Age farming activity as indicated through the pollen record and increased $\delta^{15}\text{N}$ values (as discussed in chapter 5). Chironomid assemblage data, ordination bi-plots and $\delta^{15}\text{N}$ values reflect intensification of farming at Lough Dargan and Cooney Lough during the Bronze Age. Chironomid assemblage data show increased percentages of eutrophic taxa including *Chironomus plumosus*-type, *C. anthracinus*-type, *Dicrotendipes nervosus*-type, *Glyptotendipes pallens*-type, *Cladotanytarsus mancus*-type and *Tanytarsus mendax*-type in response to farming during the Bronze

Age. PCA axis scores show a greater turnover in chironomid composition during the Bronze Age at Cooney Lough and Lough Dargan, indicating intensification (see Figure 5.5, chapter 5). RDAs established pastoral farming proxies as important drivers of chironomid community compositions at all human impacted lakes. Arable farming shows no measurable link with the chironomid assemblages, likely due to scale of activities, location relative to the lakeside or sporadic depositional pathways for cereal pollen.

The benefits of using this multi-proxy approach not only allows for the environmental impact of prehistoric farming to be assessed from a localised area, but also allows for the investigation of the permanency of the environmental impact. Findings show that Neolithic farming impacted the freshwater lake systems but to a lesser extent than during the Bronze Age. Lake sediment geochemistry and chironomid community compositions during agricultural lull in the middle Neolithic suggest that the lake systems reverted back to their pre-impacted state (i.e. similar to the late Mesolithic) at both Lough Dargan and Cooney Lough. Neolithic farming seems to only affect the lake systems temporarily, while intensive Bronze Age activity appears to alter the lake systems more permanently in the study region. This is particularly evident at Lough Dargan, where *Sergentia coracina*-type (an inhabitant of mesotrophic to oligotrophic lakes) dominated the composition during the late Mesolithic. The taxon nearly disappears from the assemblage during the early Neolithic as a result of cultural eutrophication. It then re-enters the record during the middle Neolithic lull, returning to pre-Neolithic abundances. *S. coracina*-type decreases once again to an average of 1% abundance with the onset of Bronze Age farming. At Cooney Lough, *Pagastiella*, an oligotrophic taxon described as being sensitive to both acidification and eutrophication (Brooks et al., 2007), was present during the Mesolithic (~5% abundance), and is absent from the chironomid composition by the early Neolithic period. Prehistoric farming activity thus significantly impacted the lake systems of County Sligo, permanently removing select chironomid taxa from the lake record. These findings suggest that cultural eutrophication has been a prominent influence on Irish lakes since the early Neolithic, complicating the proper establishment of natural 'baseline conditions' in Ireland (Dearing et al., 2006). The 'natural state' of Irish lakes is typically identified as pre-Industrial Revolution or mid-19th century (Leira et al., 2006), but our evidence shows substantial human impacts by the early Neolithic period; earliest environmental impact noted at Templevanny Lough at ~3790 BC.

The third research question aimed to identify indicator chironomid taxa associated with prehistoric farming, for use in future investigations. Chironomid communities responded near instantaneously to the nutrient enrichment from farming activity at each human impacted site. Large proportional shifts, typically in eutrophic chironomid taxa, were recorded in response to

cultural eutrophication at the human impacted sites (Appendix 2.4). However, specific taxon response varied from site to site. As discussed in chapter 5, *Chironomus anthracinus*-type, *Dicretodipes nervosus*-type, *Endochironomus-albipennis*-type and *Glyptotendipes pallens*-type are the main taxa at Cooney Lough that exhibit a response to farming. *Chironomus anthracinus*-type, *Glyptotendipes pallens*-type, *Cladotanytarsus mancus*-type and *Tanytarsus mendax*-type are the main responsive taxa at Lough Dargan, and *Chironomus anthracinus*-type, *Cladotanytarsus mancus*-type and *Tanytarsus lugens*-type are the main responsive taxa at Templevanny Lough. *Chironomus* is the main taxon that responds to nutrient enrichment associated with farming activity in all three studies, coinciding with major peaks in NAPp/PPI throughout. In a recent study from Lough Muckno, Ireland, *Chironomus anthracinus*-type has been identified as an indicator of increased lake productivity as a result of modern agriculture (Chique et al., 2017). It is thus suggested that *Chironomus*, taking both sub-types (*C. anthracinus*-type and *C. plumosus*-type) as a group, as well as the general eutrophic taxa mentioned above, be used as a potential indicator taxa of cultural eutrophication in Ireland for use in future investigations (Appendix 2.4). Furthermore, on multiple occasions in the human impacted lakes, LOI₅₅₀ and stable isotope data reflected inwash of terrestrial material into the lake system. Combinations of different indicator taxa of soil erosion and wood miners including *Gymnometriocnemus/Bryophaenocladus*, *Symposiocladius*, *Smittia* and *Stenochironomus* were concurrent with fluctuations in the lake sediment geochemistry (Appendix 2.4). Although these taxa are qualitatively beneficial, abundances are too low to be useful for quantitative analysis.

Differences in the responding chironomid taxa to nutrient enrichment varied from lake to lake. This is likely due to variations in the natural trophic status of the four lake systems. Palaeoenvironmental data infer that Lough Dargan was mesotrophic during the late Mesolithic, while Cooney Lough and Templevanny Lough were both relatively productive during this time. Lough Meenachrinna was oligotrophic during the late Mesolithic and for the remainder of the record. Looking at the dataset as a whole, prehistoric farming activity clearly impacted the study lakes in County Sligo. However, no two lake systems responded the same way to cultural eutrophication. This may explain the differences in the responding chironomid taxa at each site and difficulty in identifying common indicator taxa. Furthermore, no one standalone palaeolimnological proxy appears to respond consistently to anthropogenic activity, with each lake reacting slightly differently to prehistoric farming in the catchment.

7.3 Inferred findings from the control site

The addition of a control site (Lough Meenachrinna) strengthens and verifies the palaeolimnological results from the human impacted sites, validating that prehistoric farming is a strong driver of chironomid compositional change at the impacted sites. To answer the final research question, the multi-proxy approach effectively separated the human and temperature signals, allowing for the creation of a chironomid-inferred temperature estimate for the mid to late Holocene. At Lough Meenachrinna the pollen record shows minimal pastoral indicators in the early Neolithic, with increased evidence for pastoral and arable farming during the Bronze Age, and in particular the Iron Age in the catchment area. However, human activity does not appear to impact the lake system, as evident through the lake sediment geochemistry and chironomid assemblage data. Chironomid community composition infers an oligotrophic system for the majority of the record. Large shifts in chironomid taxa are not present in the mid to late Holocene and any changes in the chironomid assemblages were not concurrent with peaks in farming indicators.

Results from the control site also reinforce the relative influence of human activity as the main driver of chironomid compositional change, as discussed in both chapter four and five. If chironomid communities were responding largely to climate, synchronized shifts in the chironomid assemblages would be visible both in the human impacted sites and the control site. This is not evident in the palaeoenvironmental data, as the large proportional shifts in the chironomid assemblages, contemporaneous with increases in NAPp and $\delta^{15}\text{N}$ from impacted sites (see Figure 5.5 in chapter 5), were not present at the control site, which showed a relatively noisy chironomid community composition (see Figure 6.3 in chapter 6). Moreover, among the human impacted sites, periods of farming activity differed both in onset and longevity from catchment to catchment. As the chironomid community at Lough Meenachrinna was relatively unimpacted by farming activity, a successful chironomid-inferred temperature estimate was generated for the mid to late Holocene.

7.4 Conclusions

This PhD project set out to explore the applicability of chironomid autecology, combined with geochemical indicators, in archaeological investigation. The second objective was to provide important information about the timing, intensity and environmental impact of prehistoric farming in County Sligo, Ireland. Both objectives have successfully been achieved through completion of this article-based thesis.

This study highlights the success of applying a multi-proxy palaeolimnological approach to the area of environmental archaeology. Palaeolimnological data created a valuable insight into the

human-environmental relations of Neolithic and Bronze Age societies and the development of agriculture in the northwest of Ireland. It can be concluded that Neolithic and Bronze Age farming, in particular pastoral type farming, had a significant environmental impact on freshwater lake systems across County Sligo, leading to cultural eutrophication of lake systems and extirpation of select oligotrophic chironomid taxa. Statistical analysis verifies $\delta^{15}\text{N}$ and NApp/PPI as strong controls on chironomid community composition during the Neolithic and Bronze Age in County Sligo. To conclude, palaeolimnological indicators used in this research project have been successfully validated as a proxy for prehistoric farming. The addition of the control site verifies the findings from the human impacted sites and in doing so provided the first chironomid-inferred temperature estimate for the mid to late Holocene in Ireland. It is recommended that for future investigations of prehistoric farming and chironomid-inferred temperature reconstruction to include a multi-proxy approach of biotic and geochemical proxies in order to differentiate the climate and human activity signals.

For future investigations, there is a need for more C-IT estimates from high elevation lakes in Ireland, in order to create a regional Holocene temperature signal and rectify noise in the records from a true regional signal. The C-IT from Lough Meenachrinna not only highlights chironomids as excellent indicators of past temperature but also shows the potential for future climatic reconstruction in Ireland. In terms of future application of this multi-proxy approach, there is great potential for this methodology to be expanded not only to other areas of Ireland, but other countries for investigations of human impact including prehistoric and historic time frames. Expansion of this method could potentially be used to create baseline conditions for lakes in agriculturally impacted catchments, as well as providing valuable information on human-environment relations in the historic and prehistoric periods. In a modern ecological context, chironomid assemblage data could be used to provide information on chironomid community health and agricultural impact.

7.5 References

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Appendix 1

Abstract from the Lough Dargan paper published in the Journal of Archaeological Science (Taylor et al., 2013)

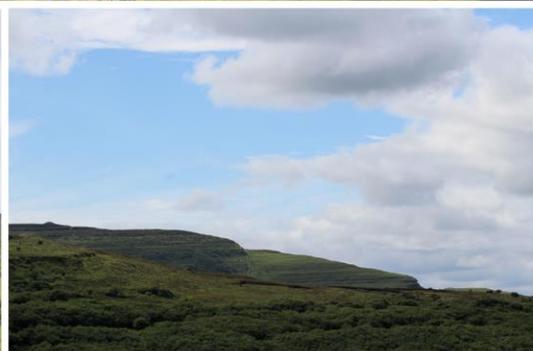
This study provides a unique method of inquiry for archaeological investigation with an aim to assess the intensity and effects of Neolithic and Bronze Age farming practices at Lough Dargan, northwest Ireland, through a multi-proxy analysis of a lake sediment core. Chironomid (non-biting midge fly) subfossils and lake sediment geochemistry ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N ratios) were used to assess changes in limnological conditions through time. The limnological data were compared with macroscopic charcoal concentration and pollen data to examine the potential influence that early farmers had on a freshwater lake system within a prehistorically active catchment. Results from the chironomid analysis show that the first substantial period of agricultural activity in the early Neolithic (c. 3730 - 3190 BC) resulted in a temporary shift to more eutrophic lake conditions. There is evidence of animal husbandry with substantial levels of animal waste reaching the lake, leaving an imprint in the geochemical record of increased $\delta^{15}\text{N}$ values and decreased $\delta^{13}\text{C}$ values and C:N ratios during this time. The chironomid community reverted back to its pre-impacted state c. 3190 BC in response to a period of reduced farming (c. 3390 - 3000 BC) which eventually led to a distinct lull in activity, with possible cessation of farming from 3000 to 2700 BC. A return to eutrophic conditions coincided with the gradual return of agriculture, with more permanently altered lake conditions dominating from 2400 BC, even during a 250-year period of reduced human activity commencing at c. 1440 BC. Increased sedimentation rate, along with increases in $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C:N, the presence of chironomid taxa indicative of erosion, more eutrophic lake conditions and high concentrations of macroscopic charcoal all point to more intensive land use practices during the Bronze Age. Palaeolimnological data exhibited an immediate response to intensified farming during this time, and were especially responsive to pastoral farming due either to scale of activity or proximity to the lakeside. The success of this study demonstrates the effectiveness of palaeolimnological analysis in the investigation of prehistoric farming. This approach will help inform Neolithic and Bronze Age land-use practice and human environment relations in the region, and highlights the potential for chironomid-based archaeological research.

Appendix 2 - Photography section (all photos taken by Karen Taylor).

2.1 Templevanny catchment and archaeology



Carrowkeel-Keshcorran megalithic complex



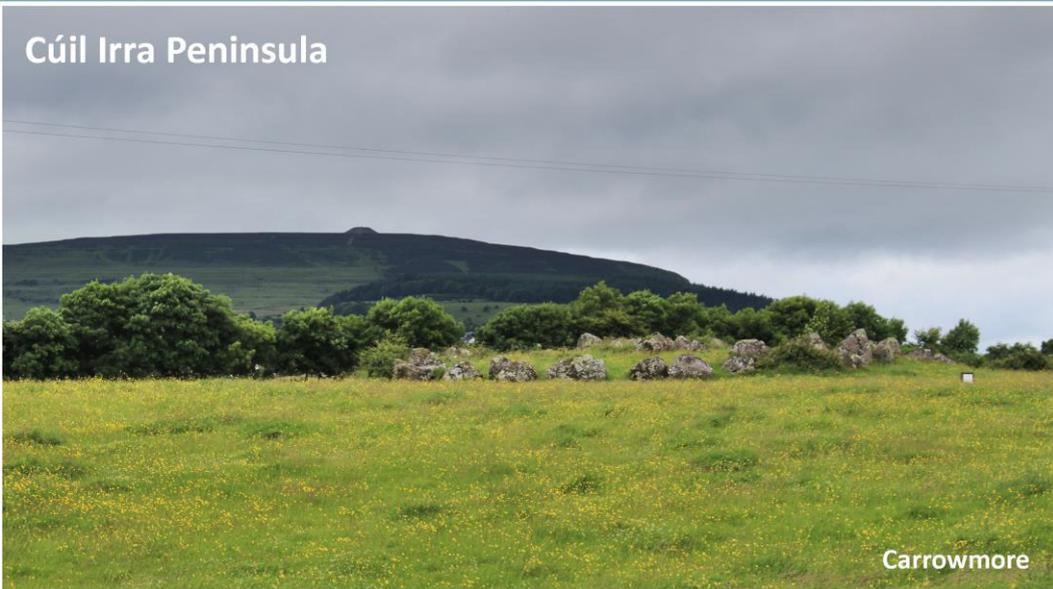
2.2 Cooney Lough catchment and archaeology

Cooney Lough



View of Knocknarea from lake

Cúil Irra Peninsula



Carrowmore



Míosgan Meabha



View from top of Carrowkeel-Keshcorran



2.3 Lough Meenachrinna catchment and fieldwork

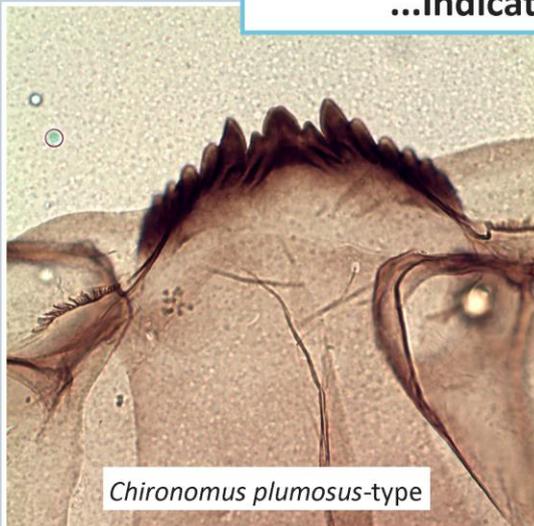


Lough Meenachrinna coring - Summer 2013

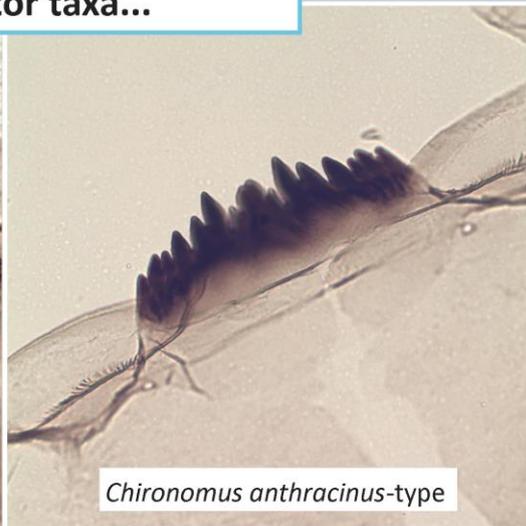


2.4 Indicator chironomid taxa

...Indicator taxa...



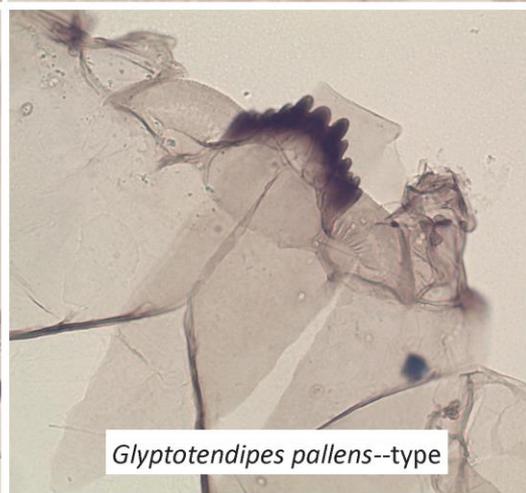
Chironomus plumosus-type



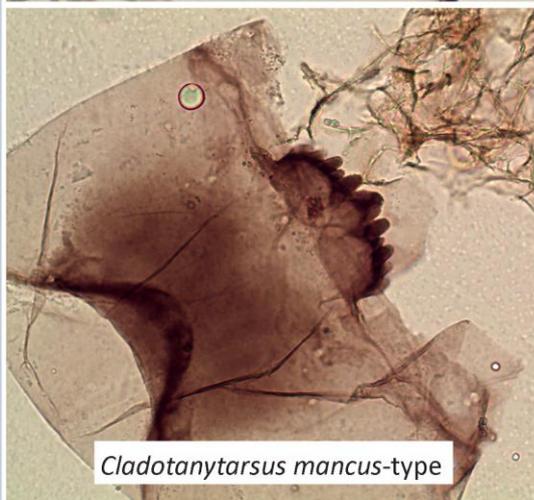
Chironomus anthracinus-type



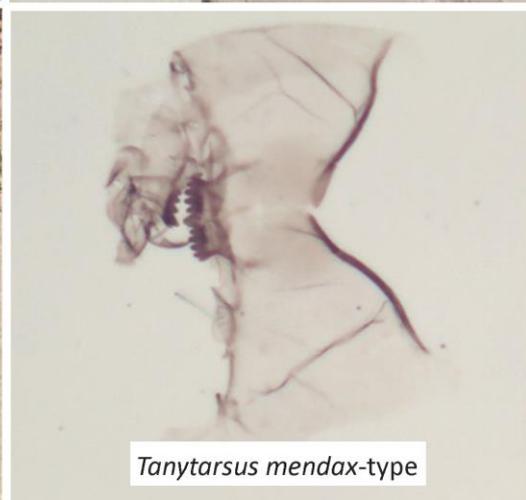
Endochironomus albipennis-type



Glyptotendipes pallens-type

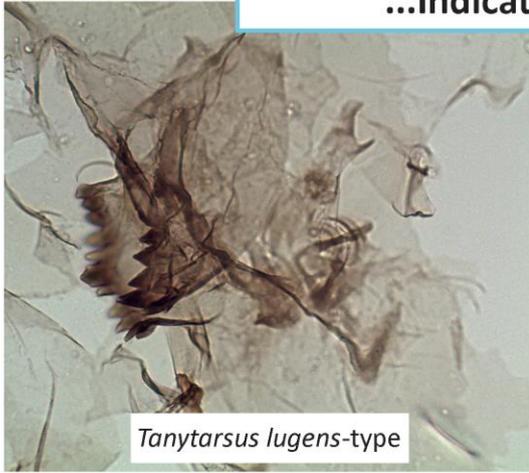


Cladotanytarsus mancus-type

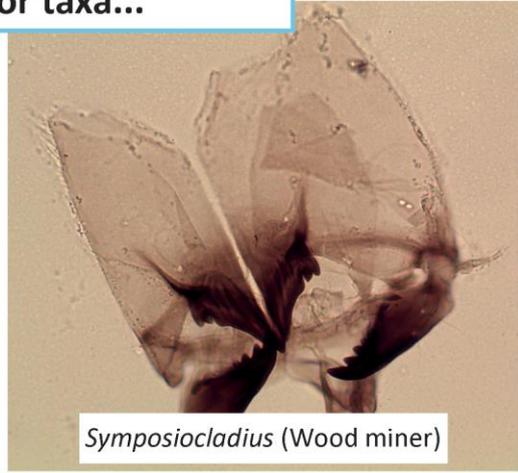


Tanytarsus mendax-type

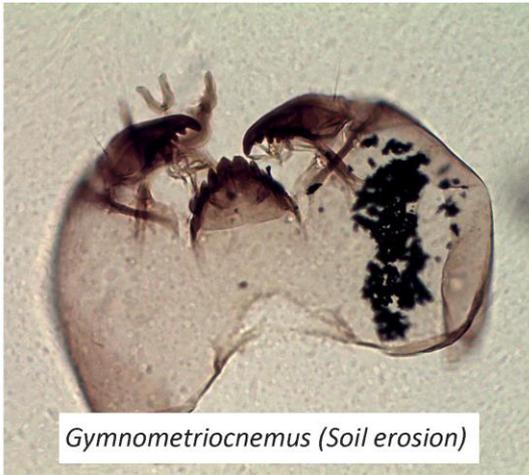
...Indicator taxa...



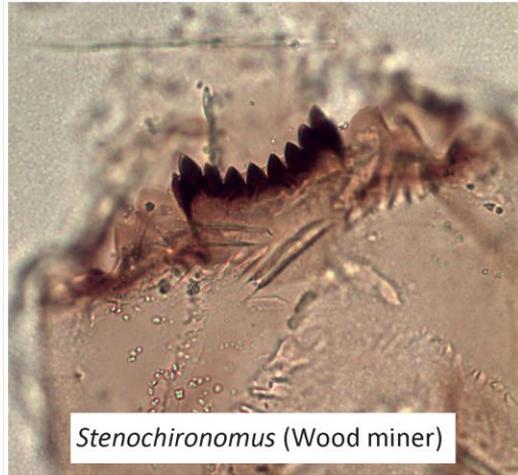
Tanytarsus lugens-type



Symposiocladius (Wood miner)



Gymnometriocnemus (Soil erosion)

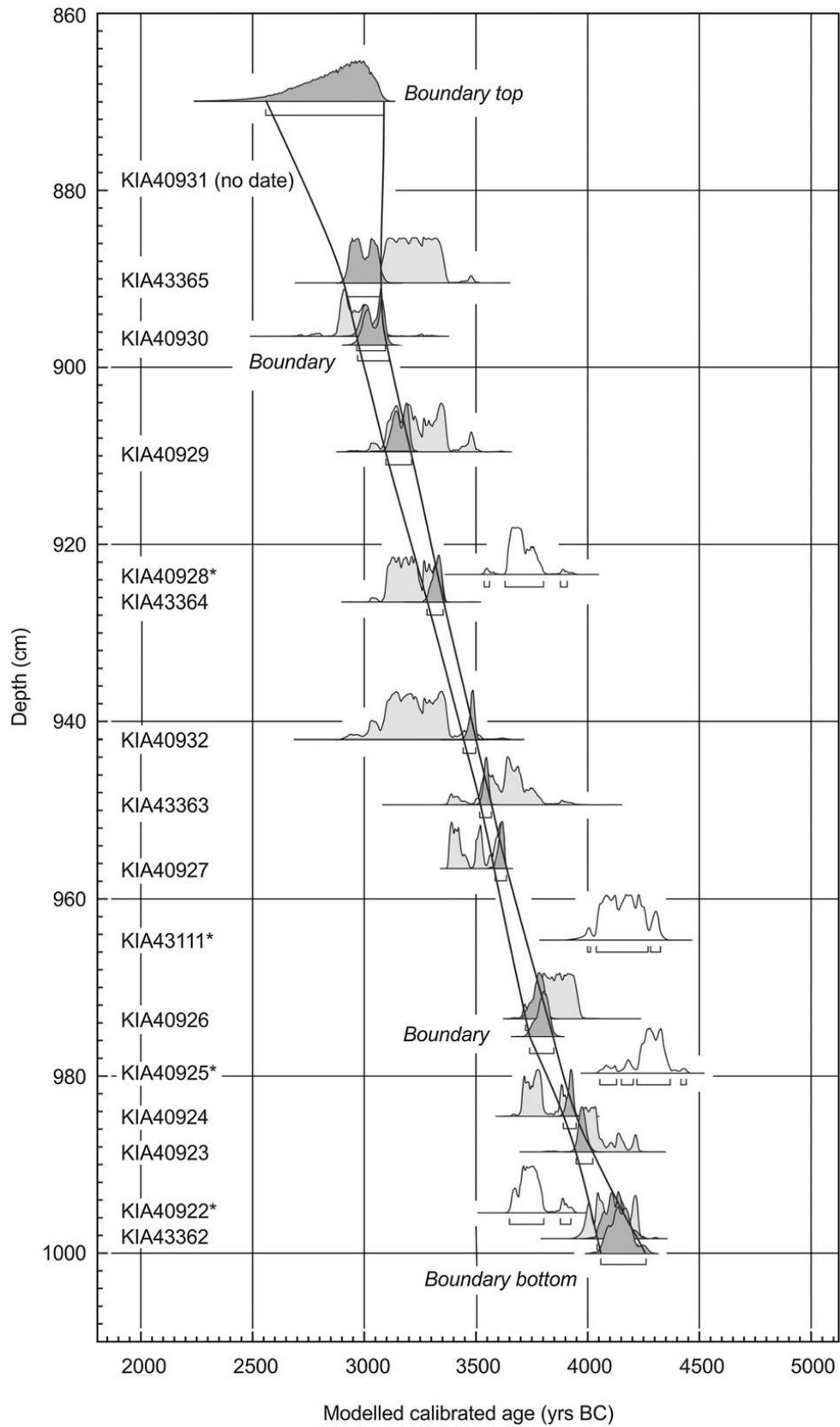


Stenochironomus (Wood miner)

Appendix 3 - Age models

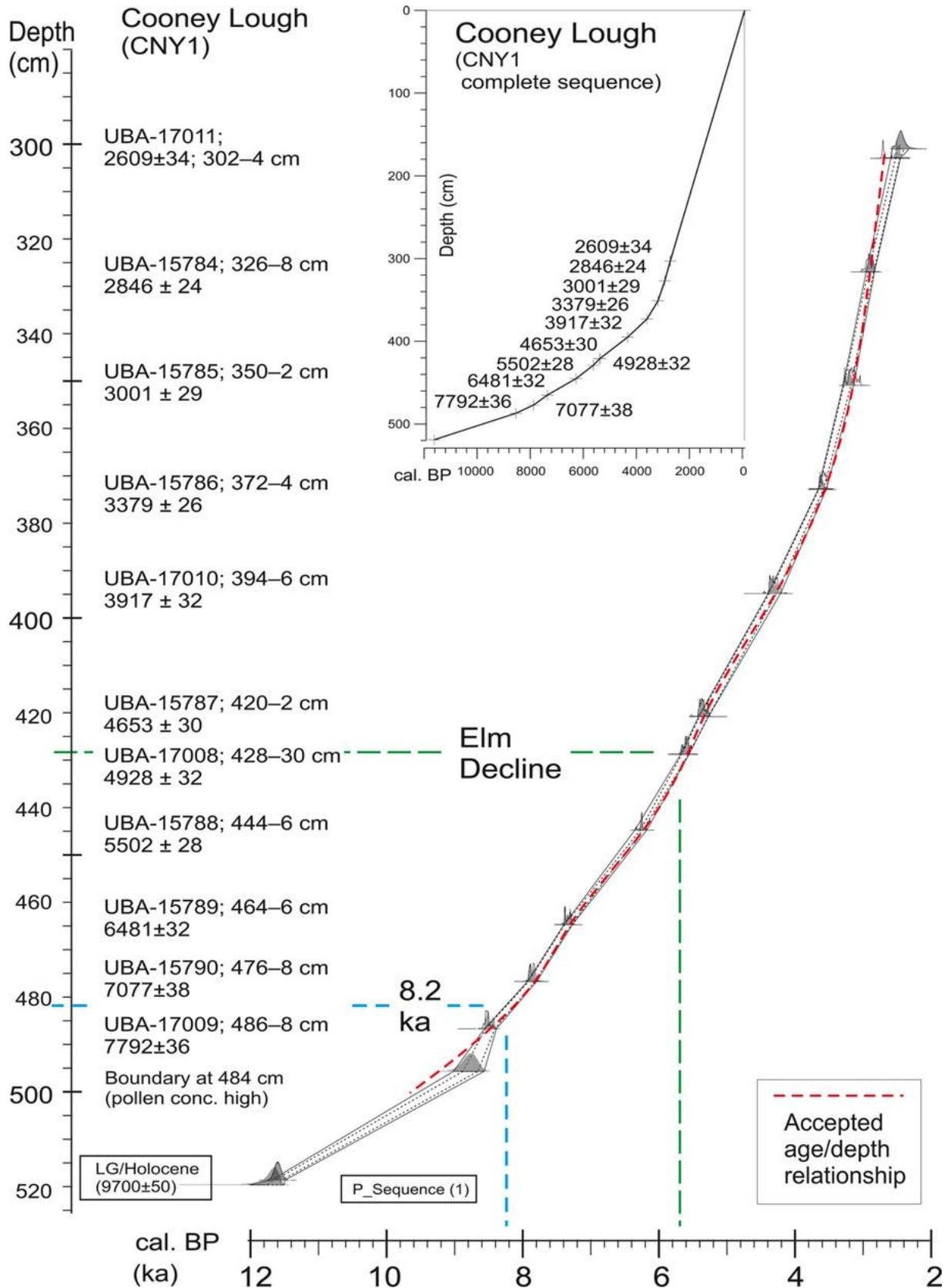
3.1 Age model for Templevanny Lough

Bayesian age-depth model for the sediment sequence from Templevanny Lough as previously published in Stolze et al. (2013). The plot shows the probability distributions for the single calibrated dates (light grey) and the posterior probability distributions taking the depth model into account (dark grey). The depth model curve envelops the 95.4% highest probability density intervals that represent a measure of uncertainty of the age estimates. Samples considered as outliers are marked with an asterisk.



3.2 Age model for Cooney Lough

Age-depth model core CNY1, Cooney Lough, based on 11 AMS ¹⁴C dates as previously published in Ghilardi and O'Connell (2013). The age-depth curve used is a spline curve fitted to the median values of the calibrated 14C dates. Output from OxCal ver. 4.1.7 is also shown including (a) an envelope showing the 95 % (solid line) and 68 % (broken line) highest probability density ranges as given by OxCal and (b) likelihood distributions of the individual dates (solid line, no shading) and also the marginal posterior distributions that take into account the depth model (shaded; terminology follows Ramsey 2008).



Appendix 4 - Raw Bacon age model output for the Lough Meenachrinna core

4.1 Settings

Settings for Bacon age model

0 #d.min
120.5 #d.max
1 #d.by
0 #depths.file
NA #slump
50 #acc.mean
1.5 #acc.shape
0.7 #mem.mean
4 #mem.strength
NA #hiatus.depths
1000 #hiatus.mean
1 #hiatus.shape
0 #BCAD
1 #cc
1 #postbomb
IntCal13 #cc1
Marine13 #cc2
SHCal13 #cc3
ConstCal #cc4
cm #unit
0 #normal
3 #t.a
4 #t.b
0 #d.R
0 #d.STD

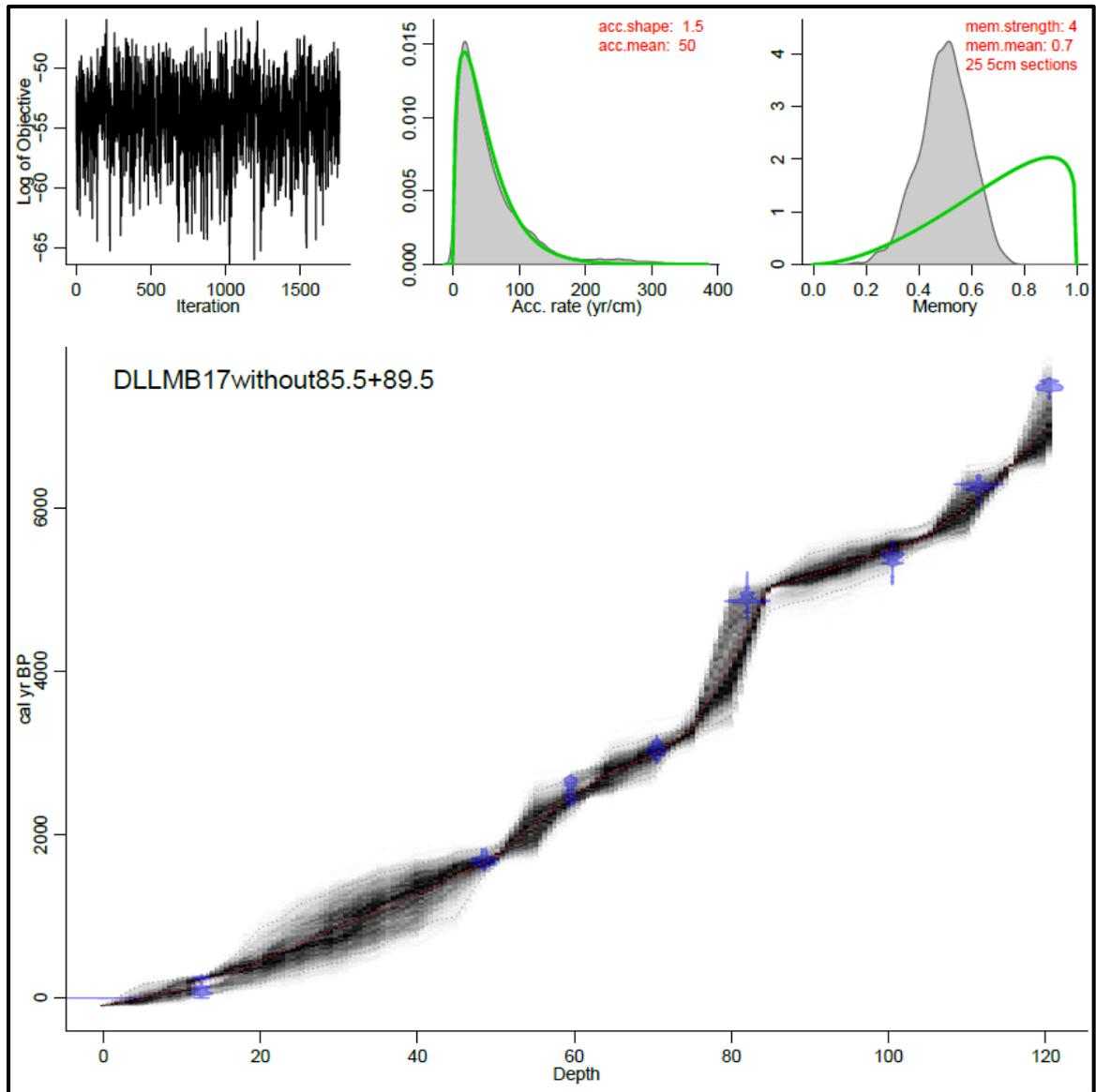
4.2 Bacon ages output for the Lough Meenachrinna core

Depth	min	max	median	wmean
0	-105.1	-78.7	-91.8	-91.5
1	-95.3	-38.4	-73.5	-71.2
2	-91.1	11.6	-56.2	-51.2
3	-88.5	63.5	-38.7	-31.1
4	-86.6	115.3	-21.6	-11.2
5	-84.1	167.2	-3.6	9
6	-66.4	177.6	18.5	28.6
7	-54.9	192.3	41.9	48.3
8	-45.6	204.2	63.1	68
9	-38.6	217	81.8	87.7
10	-32.3	245.8	98.7	107.2
11	0.3	253.2	135.9	134.8
12	27.1	262.6	185.2	162.3
13	44.5	282.4	230.9	189.8
14	57.4	335.4	252.2	216.7
15	64.6	399.9	266.1	243.3
16	97.5	450.9	297.5	283.9
17	120.1	537.4	328.5	323.7
18	139.3	635.2	360	363.5
19	156.4	749.2	391	403.5
20	168.9	859.5	421.4	443.9
21	205.6	892.5	465.5	487.3
22	234.4	938.4	508.4	530.8
23	254.4	994.1	548.8	574
24	268.9	1069.4	585.7	618.1
25	287.1	1148.1	626.7	660.8
26	331.8	1177.4	668	701.6
27	363.9	1212.7	716.2	742.1
28	388.7	1245.2	764.9	783.1
29	412.9	1286.3	807.3	823.7
30	426	1337.9	849.7	863.8
31	480.4	1370.4	890.6	904.3
32	527.2	1396.2	936.4	944.9
33	556.5	1429.9	983.3	985.2
34	588.6	1468.8	1030.6	1026.2
35	618.9	1520.1	1073	1066
36	675.8	1536.5	1112.6	1105.1
37	723.2	1559.5	1155.4	1144.1
38	756.7	1583.9	1199.6	1183.4
39	789.4	1609.5	1242.4	1222.6
40	813.6	1645.3	1283.2	1262.3

41	885.4	1657.4	1327.2	1308.1
42	931.1	1675	1374.9	1353.2
43	956.8	1697.6	1422.7	1398.9
44	974.1	1724	1471.2	1444.1
45	1002.4	1774.7	1519.8	1490.1
46	1147.4	1789.9	1558.9	1538.7
47	1299.9	1802.6	1598.4	1587.5
48	1441.1	1821.9	1638.7	1636.4
49	1548.5	1844.2	1679.5	1685.2
50	1611.6	1873	1726.6	1734.4
51	1693.1	1949.5	1808.3	1814.6
52	1727.2	2065.6	1894	1894.7
53	1752.4	2200.9	1971.8	1973.9
54	1769.9	2358.9	2050.5	2053.3
55	1786	2527.2	2129	2132.6
56	1916.5	2552.2	2197.8	2206.7
57	2032.8	2586.3	2269.6	2281
58	2135.3	2622.3	2345.8	2355.3
59	2208.3	2669.1	2420.1	2429.4
60	2272.3	2750.3	2490.7	2503.9
61	2385.9	2773.8	2536.7	2558.2
62	2464.6	2806.9	2591.3	2613.4
63	2493.6	2869.2	2655	2667.8
64	2511.4	2960.2	2718.1	2721.6
65	2526.2	3064.8	2774.4	2775.2
66	2583.5	3081.3	2813.3	2815.3
67	2618	3103	2856.3	2855.7
68	2649.2	3120.8	2899.3	2895.8
69	2672.5	3161.6	2943.8	2937
70	2699.8	3208.6	2984.6	2977.8
71	2834.7	3228.5	3040.3	3040
72	2953.8	3252.8	3096.9	3102.8
73	3034.1	3307.7	3156.3	3165.8
74	3076.1	3413.9	3217.7	3228.5
75	3102.8	3533.5	3279.1	3291.1
76	3233.4	3730.2	3464.2	3467.9
77	3303.1	3991.8	3626.1	3644.8
78	3354.9	4293.8	3782.2	3821.1
79	3400.2	4615	3937.7	3997.1
80	3442.8	4955	4100.3	4172.5
81	3757.9	4975.7	4283.4	4339.1
82	4060.4	4999	4465.7	4505.5
83	4333.3	5023.1	4652.3	4672.7

84	4566.1	5059	4842.3	4841.3
85	4745.1	5162.2	5036	5008.6
86	4778.7	5193.1	5064.3	5040.6
87	4809.8	5240.9	5088.4	5072.9
88	4834.5	5300.2	5114.1	5104.6
89	4852.9	5367.3	5140.4	5136.3
90	4864.4	5440.6	5166.5	5167.8
91	4901.6	5461.3	5196.6	5198.7
92	4938.2	5479.5	5227.8	5229.9
93	4966.2	5501.4	5259.8	5261.4
94	4991.9	5531.5	5292	5292.8
95	5012.2	5580.8	5323.1	5323.9
96	5058.2	5591.3	5355.5	5355.1
97	5105.9	5606.7	5388.6	5386.2
98	5146.2	5624	5421.5	5416.5
99	5175.5	5651.2	5456.1	5447.3
100	5207.4	5694.4	5489.1	5478.1
101	5288.4	5710.5	5516.6	5511.5
102	5359.4	5728.7	5547.4	5545.1
103	5430.7	5747.6	5579.1	5579.8
104	5487.9	5774.4	5613.6	5614.8
105	5513	5815.8	5646	5649.4
106	5568.2	5892.4	5720.8	5724.9
107	5607.1	5989.7	5799	5801.1
108	5638.2	6124.2	5871.4	5877.4
109	5663.9	6264.5	5942.3	5952.8
110	5685.8	6420.6	6012.2	6028.2
111	5830.5	6433	6094.8	6109.2
112	5968.8	6456.1	6176.7	6190.7
113	6095.2	6483.4	6261.5	6272.2
114	6198.3	6515.7	6347.9	6352.8
115	6270.7	6588.3	6433.5	6434
116	6434.1	6682.6	6548.8	6550.8
117	6493.3	6884	6655.1	6668.1
118	6527.8	7136.8	6757	6784.4
119	6553.8	7388.5	6859.3	6900.1
120	6575	7645.7	6959.9	7015.4

4.3 Original graph



4.4 References

- Ghilardi B, O'Connell M (2013) Early Holocene vegetation and climate dynamics with particular reference to the 8.2 ka event: pollen and macrofossil evidence from a small lake in western Ireland. *Vegetational History and Archaeobotany* 22, 99-144
- Ramsey CB (2008) Deposition models for chronological records. *Quaternary Science Reviews* 27, 42-60
- Stolze S, Muscheler R, Dörfler W, Nelle O (2013) Solar influence on climate variability and human development during the Neolithic: Evidence from a high-resolution multi-proxy record from Templevanny Lough, County Sligo, Ireland. *Quaternary Science Reviews* 67, 138-159