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Assessing recent climatic and human influences on chironomid communities from two moderately impacted lakes in western Ireland

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Abstract This study assessed the influences of climate warming and human impacts on Irish lakes over the late nineteenth to early twenty-first centuries. High-resolution chironomid (Insecta: Diptera) stratigraphies were developed for two low- to mid-elevation lakes in northwest Ireland to determine if lakes with mild-to-moderate human impacts can be used to accurately reconstruct mean July air temperature. Application of an Ireland-based chironomid-inference model to quantitatively estimate July air temperature ($r^2_{jack} = 0.60$, RMSEP = 0.57°C) revealed that chironomids can reflect changes in Irish temperature, particularly post-1980 when warming accelerated, although this signal becomes compromised with intensified human impacts. A biotic response to nutrient enrichment and soil erosion from direct human activities was identified through a comparison of chironomid autecology with known catchment changes. Redundancy analysis and time series comparisons were used to identify when faunal turnover is a function of local (nutrient input, erosion) versus extra-regional (climate) drivers over the recent past, and identify any thresholds of human influence within the catchments. This study highlights the importance of careful site selection as moderately impacted sites do not follow a simple scheme, as well as multi-proxy analysis to assess catchment-based human activity for longer term chironomid-based temperature reconstructions in Ireland.

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Introduction

The response of freshwater ecosystems to climate change is complex. In order to further our understanding of how ecosystem structure and function will be affected by a changing climate, and be able to develop effective mitigation strategies, we must attempt to disentangle the effects of warming from direct human impacts (Jeppesen et al., 2014). However, the task of isolating the impact of climate change from other confounding environmental variables is becoming increasingly challenging, as cultural eutrophication and warming can have a similar effect on freshwater ecology (Davidson and Jeppesen, 2013), where warming has been shown to exacerbate the effects of

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cultural eutrophication in non-nutrient-limited systems (Jeppesen et al., 2010). Time series analysis of lake records has been pivotal in extending long-term climate records, while allowing for a more intricate understanding of the potential effects of modern climate change on lake ecology (Smol and Cumming, 2008). A number of studies have attempted to separate the climate signal from anthropogenically induced pressures on lakes with mixed success (Dong et al., 2012; Thies et al., 2012; Guo et al., 2013). Jeppesen et al. (2014) suggest the use of historical climate data and palaeo-techniques to assess the impacts of local drivers versus regional climate influences. In this study, we attempt to disentangle a climate signal from changes related to direct human pressures through constrained ordination techniques and through a time series comparison with known temperature and land-use records.

Analysis of subfossil chironomids (Insecta: Diptera) provides an important tool for assessing the influence of climate change on lake ecosystems. Due to their worldwide distribution and abundance, life-cycle characteristics and mobility, as well as their sensitivity to changes in limnological conditions, chironomids have been an effective tool in reconstructing recent temperature change (Porinchu et al., 2007; Guo et al., 2013). However, studies that have employed chironomids to reconstruct recent climate change have tended to focus on regions situated in either high latitudes or high altitudes, as these areas tend to show a strong response to recent warming (Axford et al., 2009; Porinchu et al., 2010). Little research has been carried out in less extreme locations where recent warming trends are more muted, including Ireland (Leira et al., 2006). A focus on such locations would refine our understanding of chironomid sensitivity to climate change in these less extreme regions. Although chironomids are a powerful palaeothermometer, communities can be affected by a variety of environmental variables such as changes in lake productivity, pH and bottom oxygen conditions (Brodersen and Quinlan, 2006), which can potentially distort the chironomid–temperature relationship. Human influence in and around lake catchments can have a notable impact on lake conditions and is usually avoided in temperature reconstructions. For the last 6000 years, human settlement and active farming has been a prominent feature on the Irish landscape and, as a result, lakes on the island are rarely isolated from such impacts. In order to confidently reconstruct Irish temperatures through the Holocene, it must first be determined if Irish-based temperature inference models (Potito et al., 2014) can adequately reconstruct temperature at sites with low to moderate human influences.

In Ireland, chironomid research is largely restricted to temperature reconstructions over the late Glacial to early Holocene transition (Watson et al., 2010; van Asch et al., 2012) using training sets from Scandinavia and the Alpine region, and more qualitative archaeology-based studies during the Holocene (Ruiz et al., 2006; Taylor et al., 2013). Climate change in Ireland over this time remains poorly understood as the palaeoclimate record for the island is marked with ambiguity, largely due to proxy complexities, subdued temperature ranges and a prominent human influence since the mid-Holocene. Even removed from prehistoric settlement, reconstructions of relatively modest Holocene temperature change in this maritime region would prove difficult using extra-regional training sets with large temperature ranges and relatively large associated error ranges. A recent chironomid-based inference model developed from 50 lakes in western Ireland ($r^2_{\text{jack}} = 0.60$, RMSEP = 0.57°C, maximum bias = 0.63°C) may help to overcome these past difficulties in Holocene temperature reconstruction (Potito et al., 2014). The relatively small temperature range in the training set, and the accompanying small RMSEP, lends the inference model greater applicability for reconstructing Ireland's subdued Holocene temperature fluctuations (Potito et al., 2014). Furthermore, the inclusion of lakes with low to moderate agricultural impacts makes this training set more applicable to reconstructing mid to late Holocene Irish environments. Finally, the localised training set has the advantages of representing local lake types, and a more accurate representation of Irish taxa such as those associated with bogland.

This is the first study to assess the predictive ability of the chironomid–temperature transfer function using this newly developed training set for Ireland. This study systematically compared chironomid-based temperature estimates with instrumental climate data and known catchment-scale events to test the sensitivity of chironomids to recent temperature change and to determine the degree to which direct human influences are potentially confounding the chironomid–temperature relationship. The rich history of human interaction and the close association of Irish climate with north Atlantic phenomena make western Ireland a unique location for chironomid-based palaeolimnological research, and ideal for modern studies of complex human–climate–lake interactions.

Study sites and land-use histories

Ireland has a maritime climate with mild wet winters and cool moist summers (Met Éireann, 2015). The island is situated on the western edge of Europe and is, therefore, strongly influenced by the Atlantic Ocean with notable long-term periodicities linked to the North Atlantic Oscillation (NAO). July temperatures average ~16°C, while average January temperatures are ~7°C (Met Éireann, 2015). Warming in Ireland has followed global temperature change quite closely, with mean annual temperatures increasing by 0.7°C since 1900 (Sweeney et al., 2008).

Atlantic blanket bogs and mountain blanket bogs cover most of the western Ireland landscape, and agriculture, especially pastoral farming, is widespread across the region. Therefore, the majority of Irish lakes have some degree of human activity in their catchments. Two study sites were chosen to represent low to mid-elevation small Irish lakes with low to moderate human activity in their catchments (Fig. 1A). These lakes were also selected due to their proximity to the Markree Observatory (36 m a.s.l.; 28.2 km from Lough Meenagraun and 3 km from Lough Ballygawley), where monthly temperature records have been established dating to 1842 (McKeown et al., 2012).

Lough Meenagraun

Lough Meenagraun (54°22.94′N, 8°12.98′W) is a small (3 ha), shallow (max depth of 2.1 m) lake and is considered a mid-elevation site (379 m a.s.l.). It is situated in the remote mountainous rural district of Glenade, County Leitrim on a landscape comprising pale orthoquartzitic sandstone (Geological Survey of Ireland, 2013), overlain with peat bog (Fig. 1B). The contemporary lake is classified as oligotrophic/mesotrophic as concentrations of nitrate <0.2 mg/l, nitrite <0.002 mg/l, total phosphate <0.05 mg/l and ortho phosphate <0.05 mg/l. As the surrounding catchment comprises bog, the lake water is acidic with a pH of 4.5. The lake has an oval asymmetrical shape with notable shelves on the northern, southern and south-eastern sides (Fig. 1B). On the southeastern shelf, the morphology of a previously active small (<0.5 m wide) outlet stream is evident. The rocks and boulders along the southeastern shelf essentially damn the outlet channel. The angular nature and 'fresh' surface of the boulders means it is unlikely that they were deposited *in situ* during the last Ice Age. It is more likely that their existence at this location is as a result of human activity sometime in the recent past. Vegetation surrounding this lake is dominated by *Sphagnum* and *Calluna vulgaris,* which are typical of Irish mountain bog landscapes.

Despite the remote location of the lake, pastoral farming exists in this area. Farm animals such as sheep and rams are present on the surrounding mountainous landscape. The lake is enclosed by a fence, built to prevent mixing of farm animals. This enclosure, known as a sheepfold (Hever, 1980), is not solely a modern fixture and has historic affiliations (National Monuments Service, 2013). An article in a local newspaper, *The Leitrim Advertiser*, dating to Thursday, August 2nd 1894 states that "wool is one of the principal products of the neighbourhood (townland)", indicating the importance of its production in a largely agricultural society of the late nineteenth century. Evidence of population change at an Electoral District level illustrates that the total population in this area fell from 1213 to 964 between 1841 and 1851, respectively, coinciding with the Great Famine of 1845–1849 (Fotheringham et al., 2011). This famine comprised one of the most significant human disasters of the nineteenth century and resulted in the dramatic depopulation of the Irish landscape, particularly the western portion of the Island. Total population continued to fall to 930 by 1861 before increasing to 1050 in the 1870 s and 1880 s. By 1900, the total population of the area declined even further to 640, and continued to decrease throughout the twentieth century falling to levels of 153 by 2002. Through a comparison of a 1907 Ordnance Survey Ireland map (Fig. 1D) with modern orthographic photograph of the Lough Meenagraun catchment (Fig. 1E), it was clear that no notable landscape change occurred over the twentieth to early twenty-first centuries.

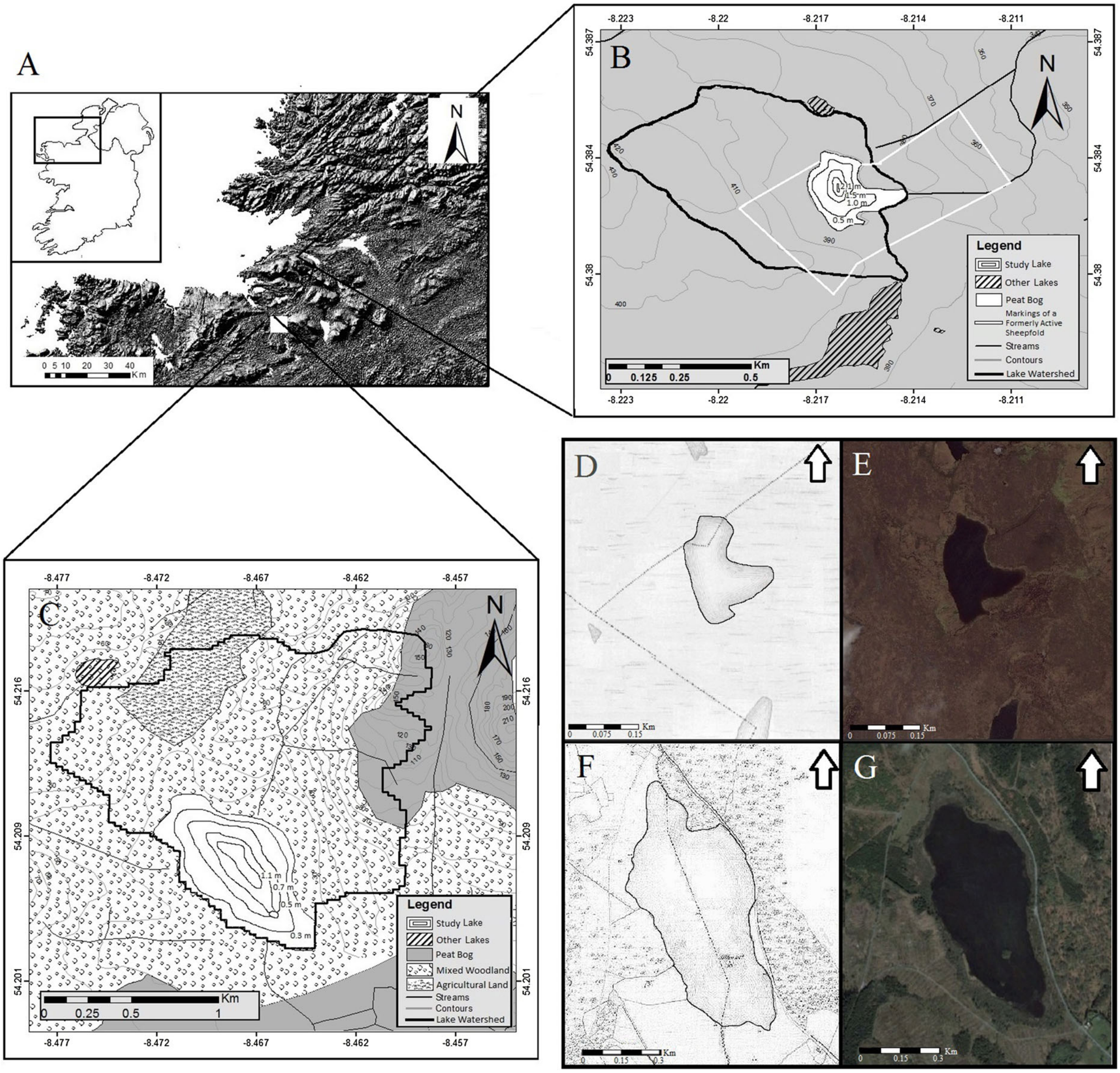


Fig. 1 **A** Map of northwest Ireland with study sites highlighted. *White square* represents the location of the Markree meteorological station. **B** Contemporary land-use characteristics of Lough Meenagraun. **C** Contemporary land-use characteristics of Lough Ballygawley. **D** Hand-drawn map of Lough Meenagraun dating to 1907, modified from Ordnance Survey Ireland. *Grey line* indicates political land divisions. **E** Modern orthographic photograph of Lough Meenagraun modified from Google Earth. **F** Hand-drawn map of Lough Ballygawley dating to 1907, modified from Ordnance Survey Ireland. *Grey shading* indicates forest cover. **G** Modern orthographic photograph of Lough Ballygawley modified from Google Earth. *Darker areas* indicate forest cover, while the *lighter areas* are indicative of bare land

Lough Ballygawley

Lough Ballygawley (54°12.44′N, 8°28.12′W) is a large (26.7 ha), shallow (max depth of 1.1 m), low elevation lake (26 m a.s.l.) (Fig. 1C). It is situated in a calcareous area that overlies gneiss bedrock (Geological Survey of Ireland, 2013), giving the water a pH of 7.8. The contemporary lake is classified as oligotrophic/mesotrophic as concentrations of nitrate <0.2 mg/l, nitrite 0.004 mg/l, total phosphate <0.05 mg/l and ortho phosphate <0.05 mg/l. Lough Ballygawley displays a sub-rectangular shape, and the transition from this deepest region of the lake to the shallowest zone (<0.3 m) is marked by gentle slopes on all sides. A human-made artificial island, formerly a Medieval or Neolithic dwelling (Edwards, 2013), protrudes in the southern portion of the lake, and has not been active over the time period of this study. The northeastern shore has an active inflow stream, and two small outflows, on the southern and western shores.

The lake is situated 2.5 km northeast of Collooney town, County Sligo, beside a regional class road, and modern human impacts are a discernible feature at this site. The lake is situated within a forested area, Union Wood, which is managed by Coillte.[1] Lake drainage, agriculture and forest management are the primary activities that have taken place at this site since the mid-nineteenth century. O'Rourke (1889) states that between 1860 and 1888, forestry expansion took place in the lake catchment. Evidence contained in the 1907 Ordnance Survey Ireland map displays the areas of land covered with forestry (Fig. 1F). Further evidence in an orthographic photograph from 2009 (Fig. 1G) demonstrates the intensity of recent forest management, with substantial clearance taking place at the eastern and western areas of the woodland bordering the lake. Forest expansion occurred in all other areas around the lake since the 1990 s. The dominant tree species in the catchment are *Picea abies, Betula pendula, Fagus sylvatica* and *Abies procera.* The lake is fringed by open reedswamp in which *Phragmites* and *Scirpus* are present, while the water itself is mesotrophic, with 3 mg l^{-1} suspended solids and a conductivity of 115.8 µS cm^{-1}.

Evidence derived from historical documents has allowed land-use and hydrological histories over the recent past to be pieced together. The modern orthographic photograph (Fig. 1G) shows the existence of arable cultivation ridges, commonly called 'lazy beds', which are particularly associated with agriculture in Ireland in the nineteenth century (Bell, 1984). This provides evidence of farming activity around the lake in the early to mid-nineteenth century. The extinction of *Lobelia* in the 1980 s, likely as a result of run-off entering this lake, provides evidence of more recent agricultural activity (Douglas et al., 1993) around Lough Ballygawley. According to Woodmartin (1886), the lake was drained in the late nineteenth century, while a report for the National Parks and Wildlife Service states that the lake was drained again in the early 1920 s (Goodwillie et al., 1992). Due to the location of the site, in an area subjected to vegetation removal and human disturbance from the nearby road, this lake experiences a higher level of contemporary human activity compared to Lough Meenagraun.

[1] Coillte is a commercial company that owns approximately one million acres of land throughout Ireland.

Materials and methods

Field

In autumn 2009, duplicate sediment cores were extracted from the centre of Lough Meenagraun (2.1 m depth) and Lough Ballygawley (1.1 m depth) using a Glew mini-corer (Glew, 1991) deployed from an inflatable raft. Core lengths were 20 and 26 cm for Lough Meenagraun, and 19.5 and 21.5 cm for Lough Ballygawley. Each of the cores was sectioned at the lakeside at 0.5 cm intervals, placed in clearly labelled sample bags and transported to the National University of Ireland Galway. All dating and analysis was limited to the longer core from each site in order to avoid errors in interpretation.

Laboratory

Radioisotopic ages were obtained using ^{210}Pb, which can reliably date sediments to ca. 150 years before present (Appleby, 2013). Thirteen bulk sediment samples from Lough Meenagraun and twelve from Lough Ballygawley were analysed for ^{210}Pb content. Samples were chosen using an exponential depth sequence, and analysis was carried out by MyCore Scientific, Inc., Deep River, Ontario, Canada. ^{210}Pb ages were calculated using the constant rate of supply (CRS) model (Appleby, 2013), and age-depth models were constructed using SigmaPlot version 10.

Loss-on-ignition (LOI) analysis (Heiri et al., 2001) was carried out at 0.5-cm intervals to establish percent organic and inorganic carbon content throughout each of the cores from both sites. Chironomid analysis followed standard procedures outlined by Walker (2001), where head capsules were handpicked at 0.5-cm intervals over the ^{210}Pb dated portion of each record and then at 1 cm intervals below this zone. At each depth range, the least amount of sediment was used to extract the desired amount of 50 head capsules. While taxa ecology based on Wiederholm (1983), Rieradevall and Brooks (2001) and Brook et al. (2007) offered valuable information at genus, sub-genus and species level, it was essential to examine ecological preferences of taxa within an Irish context. The chironomid taxa identified in the Irish training set (Potito et al, 2014) are well-represented downcore in Lough Meenagraun and Lough Ballygawley. Consequently, ecological optima and tolerances established for each taxa in this Irish training set were used to further determine ecological preferences.

Numerical and statistical methods

The chironomid percentage diagram was constructed using C2 version 1.4, and zonation of chironomid percentages was performed using Psimpoll 4.27 (Bennett, 2009). Zonation was based on sum-of-squares partitioning, and statistical significance of zones was determined using BSTICK (Bennett, 1996). All ordinations were produced using square-root-transformed chironomid percentage data for all common taxa. Common taxa from each lake were identified as those present in at least two samples with a relative abundance of 2% in at least one sample. To provide a deeper exploration of the relationship between chironomid community change and climate variables in the ^{210}Pb-dated sections of the cores, redundancy analysis (RDA) was performed. As the Markree Observatory temperature and precipitation data extend to 1880, all RDAs were carried out from 1880 to 2009. Partial RDAs were then used to examine the relative importance of each variable. Canonical coefficients, t tests and eigenvalue ratios (λ_1/λ_2) for each of the selected variables were used to determine the primary environmental controls for each of the chironomid profiles in both lakes. All ordinations were performed using CANOCO version 4.5.

Chironomid-inferred mean July air temperature estimates (C-IT) for Lough Meenagraun and Lough Ballygawley were generated from a modern calibration set of 50 Irish lakes (Potito et al., 2014), covering a mean July temperature range of 11.9–15.6°C. The weighted-average classical inference model for mean July air temperature (Potito et al., 2014) was applied to the both chironomid stratigraphies to reconstruct the thermal regime for each lake spanning the interval for which a reliable radiometric chronology could be developed. A LOESS smoother was applied to both reconstructions to emphasise dominant trends in both datasets. Sample-specific errors were 0.57°C. A goodness-of-fit test was used to assess whether the downcore assemblage in both lakes are adequately represented in the Irish training set model. Here, the Chi squared residual distance of the surface and downcore samples was plotted passively using canonical analysis (CA), following Birks et al. (1990), Birks (1998) and Heiri et al. (2003). A cut-level of the 10th and 5th percentile in the modern residual Chi square distances was chosen for samples with a 'poor' 'and a very poor' fit to temperature, respectively.

To explore the chironomid–climate relationship through time, chironomid-inferred temperatures (C-IT), PCA Axis 1 scores, organic carbon (550°C) and dry mass accumulation rates (DMAR) were examined along with Markree mean summer temperature (June, July and August), mean July air temperature, the warmest average July temperature for each sample interval, seasonal and annual precipitation and winter North Atlantic Oscillation (NAO) index values. The NAO index values, which have the strongest influence on winter climate (McKeown et al., 2012), have been shown to have an influence on precipitation patterns, which could in turn have a discernible impact on biological activity within lakes (Jennings et al., 2000; Livingstone et al., 2010).

In order for such a comparison to be possible, all data were adjusted to match the resolution of the lake sediment samples. For Lough Meenagraun, each 0.5 cm section of the lake sediment represents between 1 and 6 years of sedimentation after 1975, and 16–23 years in the lower portion of the sediment core. For Lough Ballygawley, each 0.5 cm section of the lake sediment represents between 1 and 5 years of sedimentation after 1962, and 6–12 years in the lower portion of the core.

Results

Dating model

For Lough Meenagraun, the top 8.5-cm section of the core was datable by ^{210}Pb and represents 1860–2009 (Fig. 2A). Standard errors (SE) of ^{210}Pb dates ranged from 83 years at the bottom of the chronology to

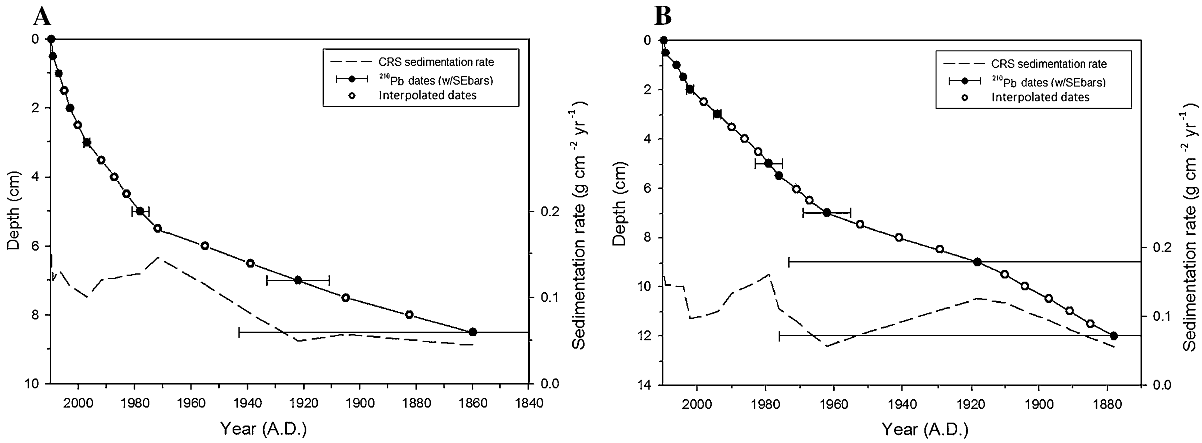


Fig. 2 ^{210}Pb age-depth models for **A** Lough Meenagraun and **B** Lough Ballygawley using the CRS model

approaching zero error at the top of the core. The mean dry mass accumulation rate (DMAR) varied over the core from the mid-nineteenth century to present. From 1860 up until 1922, the lake was characterised by a steady low dry mass accumulation rate (DMAR) of 0.033 g cm^{-2} year^{-1}, with a notable increase from the 1920 s to 0.093 g cm^{-2} year^{-1}. For Lough Ballygawley, the top 12-cm section of core A was datable by ^{210}Pb and represents 1878–2009 (Fig. 2B). SE of ^{210}Pb dates ranged from 98 years at the bottom of the chronology to approaching zero error at the top of the core. Sedimentation rates vary considerably over this dated section of the core. The 1960–2009 period displays enhanced variability in DMAR, with brief episodes of sediment accumulation occurring in the late 1970 s (0.161 g cm^{-2} year^{-1}) and after 2004 (0.143 g cm^{-2} year^{-1}).

Chironomid percentage diagrams

The average number of head capsules enumerated per sample was 77 from Lough Meenagraun and 69 from Lough Ballygawley. Due to low abundance of midge remains at certain sample depths from the Lough Ballygawley core, the minimum requirement of 50 head capsules could not be recovered from five samples. In these samples, 40–49.5 head capsules were extracted, and although this is not desirable, it is still statistically viable (Larocque et al., 2001). In total, 41 different taxa were identified from the Lough Meenagraun core, with an average of 21 taxa per sample. Zonation for the entire core was significant at two zones, with a boundary occurring at 9.5 cm depth, just before the ^{210}Pb-dated portion of the core (Fig. 3A). Zone boundaries, although not significant, also occurred at 7.5-cm depth and 4.5-cm depth, 1894 and 1985, respectively. Organic carbon values range from 27 to 91% throughout the core. Values remain relatively low towards the bottom of the core, with a gradual increase until 12 cm. The level of organic carbon abruptly increases at 12 cm until it stabilises at 8.5 cm. The Shannon–Wiener diversity index ranged from 2.9 to 4.9. The chironomid assemblages in Lough Meenagraun show a notable shift in community composition between zones 1 and 2. *Microtendipes pedellus*-type, *Tanytarsus pallidicornis*-type, *Polypedilum nubifer*-type and *Corynoneura edwardsi*-type all increase in abundance in zone 2. *Heterotanytarsus* also shows a marked increase from zone 1 to zone 2. This taxon remains prominent in zones 3 and 4, but becomes progressively less abundant throughout these zones. *Limnophyes/Paralimnophyes*, *Parametriocnemus/Paraphaenocladius* and *Pseudsmittia* peak in abundance at the start of zone 2. *Tanytarsus mendax*-type, *Dicrotendipes nervosus*-type and *Cladotanytarsus mancus*-type are present in large numbers in zone 1 and show an overall decrease throughout zone 2, before increasing again in zones 3 and 4. Zone 1 contains the highest level of *Stictochironomus rosenschoeldi*-type, *Heterotrissocladius grimshawi*-type, *Heterotrissocladius marcidus*-type and *Psectrocladius septentrionalis*-type. These taxa remain dominant

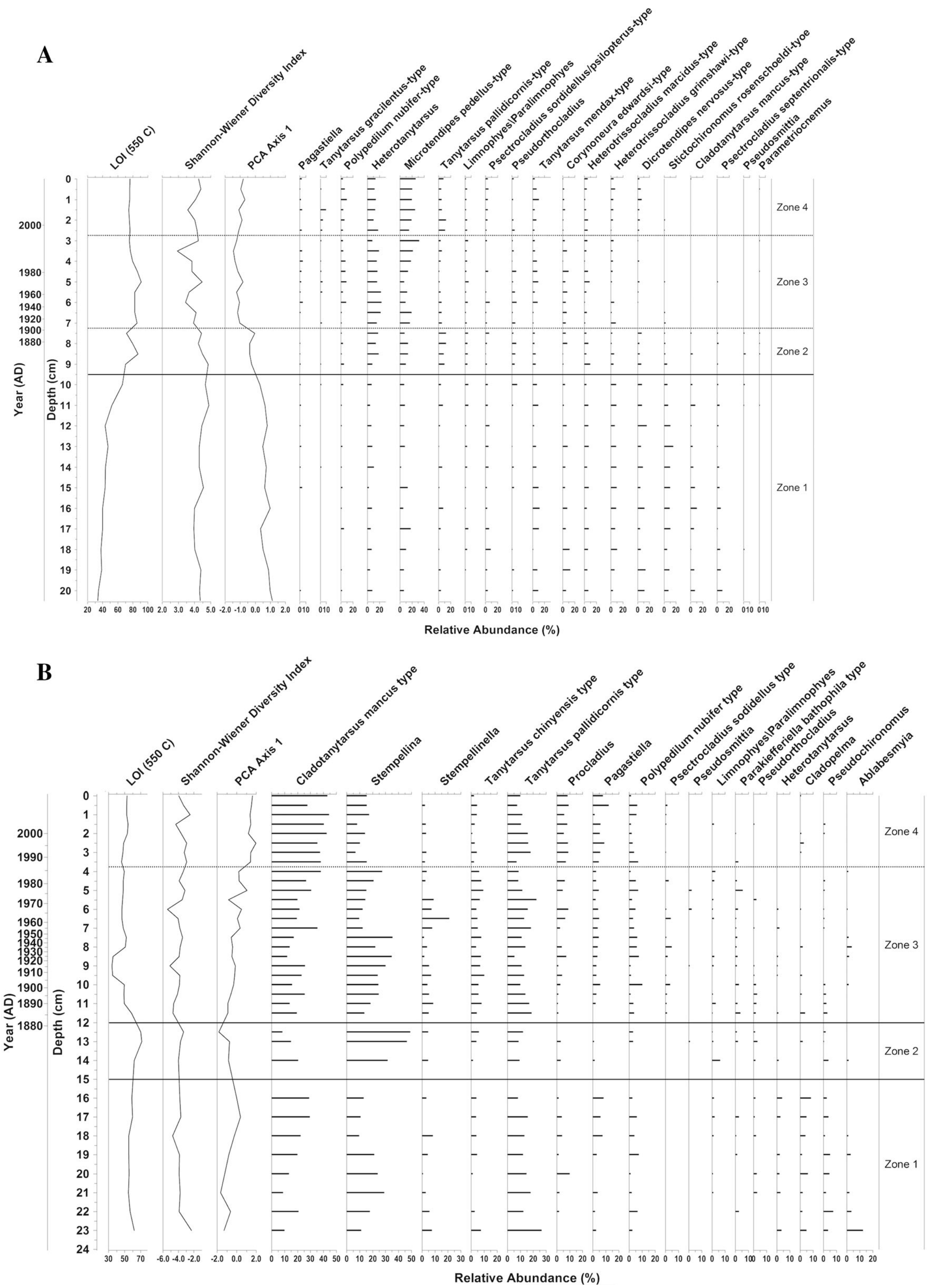


Fig. 3 Chironomid stratigraphy for **A** Lough Meenagraun and **B** Lough Ballygawley

in zone 2; however, they drop in abundance and persist at low levels in zones 3 and 4.

A total of 57 different taxa were identified through the Lough Ballygawley core, with an average of 18 taxa per sample. Two zone boundaries were significant, at 15.5 and 12.5 cm, respectively (Fig. 3B). Head capsule concentrations varied widely throughout the core with 14–46 head capsules per ml of wet sediment. The Shannon–Wiener Diversity Index ranged from 2.5 to 5.4. The greatest level of diversity was observed in zone 4, while zone 1 marked the lowest diversity levels. LOI_{550} remains relatively consistent throughout zone 1, averaging around 56%, and increases throughout zone 2, with an average of 65%. The end of zone 2 marks the beginning of the ^{210}Pb-dated chronology. LOI_{550} is marked by an initial falling episode for the first third of zone 3, reaching its lowest levels between 1910 and the mid-1920 s. Organic content remains stable at ~51% throughout the rest of the core.

Tanytarsus pallidicornis-type, *Cladopelma*, *P. nubifer*-type and *Procladius* show an overall increase throughout zone 1. *Stempellina* shows an inverse trend to *Stempellinella*. This is evident in zone 2, where there is a notable increase in *Stempellina* and a decrease in *Stempellinella* and *T. pallidicornis*-type. *Stempellina* decreases in zone 3 and continues to decline in zone 4, while *T. pallidicornis*-type, *Procladius* and *P. nubifer*-type increase to almost a third of the entire chironomid population in zones 3 and 4. *Limnophyes/Paralimnophyes* and *Pseudorthocladius* reach their highest levels between mid-1880 s and early 1900 s. *C. mancus*-type, *Pagastiella* and *Ablabesmyia* are the most prominent taxa in zones 1, 3 and 4, and account for almost half of total chironomid population.

Chironomid-inferred temperature reconstructions

The downcore midge assemblages from Lough Meenagraun and Lough Ballygawley were plotted passively against the assemblages in the western Irish training set to determine if the midge communities in both lakes were represented in the regional training set (Fig. 4). The CA shows that the downcore composition of the nineteenth to early twenty first century midge assemblages in Lough Meenagraun and Lough Ballygawley is located within the ordination space captured by the western Ireland training set (Potito et al., 2014). One sample in the Lough Meenagraun core and two samples in the Lough Ballygawley core showed a 'poor' fit to July air temperature (Fig. 5), and only one sample (the surface sample) in the Lough Meenagraun core showed a 'very poor' fit to temperature. All other samples showed a 'good' fit to temperature.

The chironomid-inferred temperature model (C-IT) for the dated portion of Lough Meenagraun ranged from 12.4 to 13.2°C between 1868 and 2009, with a notable warming rate of 0.13°C/decade from the 1970 s to 2009 (Fig. 5); accelerated warming is evident from the 1990 s to 2009 at a rate of 0.27°C/decade. For Lough Ballygawley, C-IT ranged from 14.3 to 15.3°C between 1878 and 2009 (Fig. 5). The time period between the early 1970 s and 2009 displays a rate of warming of 0.11°C/decade, and accelerated warming is evident in the more recent decades at a rate of 0.34°C/decade from the 1980 s to 1990 s. Overall, a notable warming trend is evident in both reconstructions, where the warmest years span 1990 to 2006, while cooler C-ITs are present in the late nineteenth and early twentieth centuries. This follows the temperature trend evident in the Markree decadal summer record, with cooler summers evident in the 1900 s, 1910 s and 1920 s (McKeown et al., 2012). Summer temperatures increase briefly from the mid-1920 s until the mid-1930 s before gradually decreasing until the mid-1970 s. Annual summer temperatures become more variable from the 1970 s until the mid-1980 s, before accelerated warming from mid-1980 s. The warmest decades in the Markree annual record are the 1990 s and 2000 s (McKeown et al., 2012).

For the Lough Meenagraun C-IT, no synchronous patterns were evident between precipitation values, NAO index values and trends in chironomid PCA Axis 1, sediment LOI_{550} and DMAR (Fig. 6A). Organic carbon appears to be following chironomid PCA Axis 1 scores in the earliest portion of the stratigraphy from the late nineteenth century until the mid-1950 s, indicating that lake productivity or catchment erosion is likely influencing the chironomid community in this section of the core. Hereafter, summer temperature appears to be the most important variable as a clear correspondence is evident between C-IT and Markree temperature trends. The Lough Meenagraun C-IT appears to be following the mean July temperature record more closely than the mean summer

Fig. 4 Correspondence analysis (CA) passively plotted midge assemblages from Lough Meenagraun and Lough Ballygawley with chironomid assemblages present in the Western Ireland training set (Potito et al., 2014)

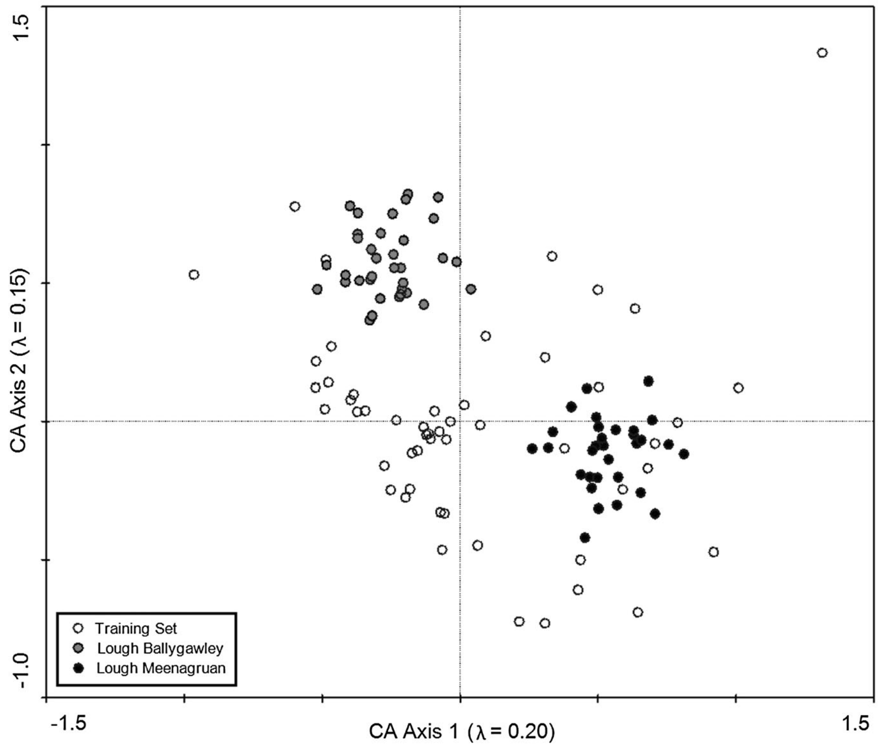
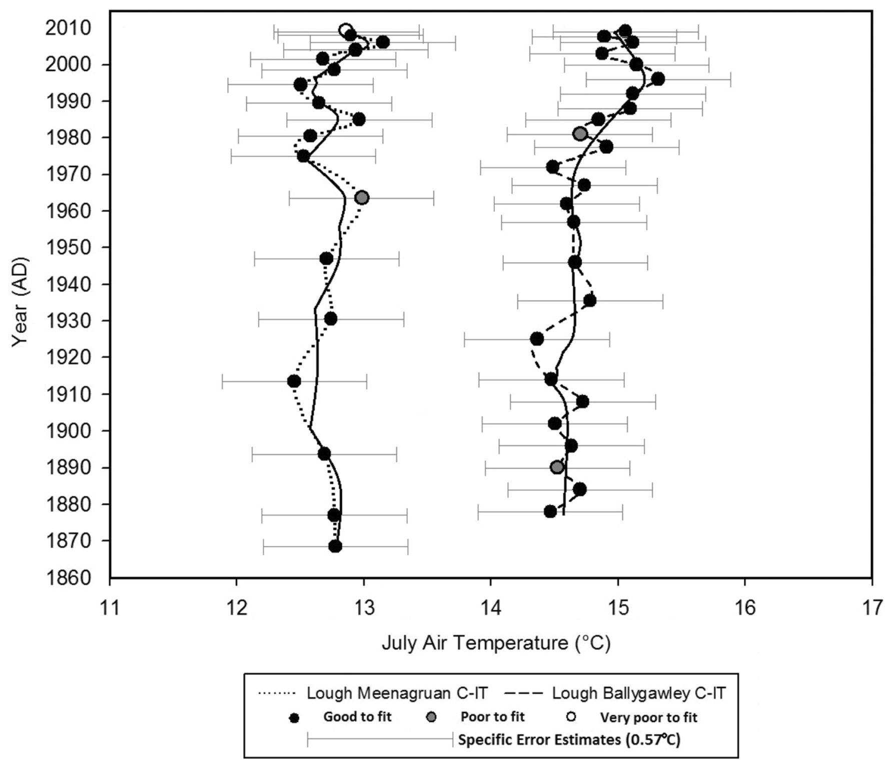


Fig. 5 Chironomid-inferred mean July air temperature (C-IT) reconstruction for Lough Meenagraun and Lough Ballygawley spanning the ^{210}Pb chronologies. The *solid black lines* represent LOESS smoothers (0.3). The *black dots* represent goodness-of-fit with the 50-lake Irish training set (Potito et al., 2014)



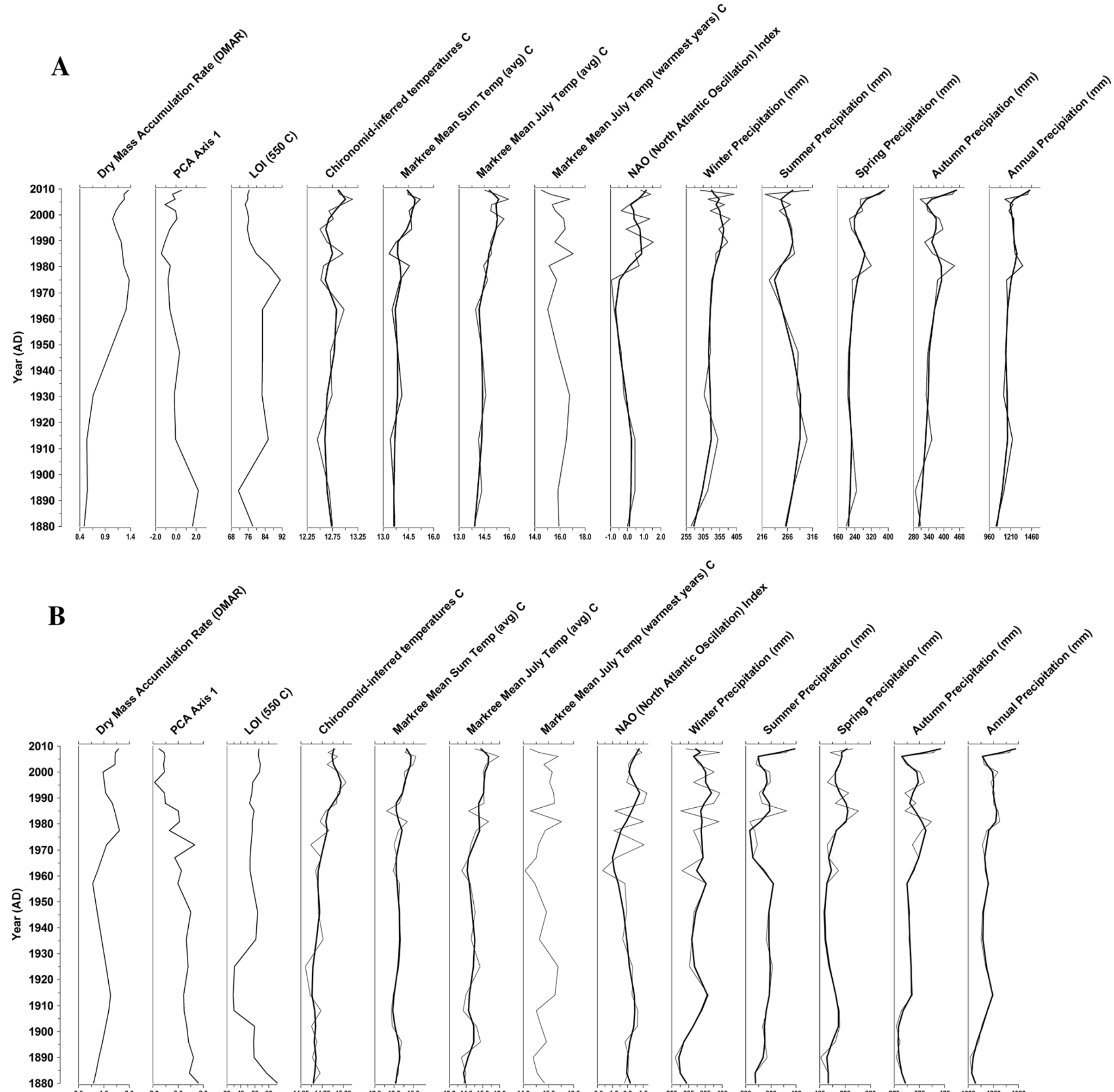


Fig. 6 Chironomid-inferred mean July air temperature (C-IT) reconstruction of Lough Meenagraun (**A**) and Lough Ballygawley (**B**), chironomid PCA, LOI_{550}, DMAR, compared to Markree summer temperature, seasonal precipitation and NAO index. Climate data are averaged over each sampling interval

temperature record over the entire twentieth century. Temperature change in the early-twenty first century is similar in all records, where temperatures increase to 2006, before falling to 2009. Furthermore, the warmest average July temperatures in each sampling interval correspond with the high values seen in the chironomid-inferred temperature reconstruction in the mid-1980 s, the 1990 s and mid-2000 s. For Lough Ballygawley, summer temperature appeared to be the most important variable on the chironomid–temperature model; a further correspondence is evident with C-IT and the inverse PCA Axis 1 values (Fig. 6B). All other variables showed no synchronous trends with the C-IT. Enhanced warming is evident in the Lough Ballygawley C-IT after 1850, which is evident in all three Markree temperature records. Although trends are similar to the Lough Meenagraun C-IT, the temperature variability in the Lough Ballygawley C-IT is more muted.

Redundancy analysis

Redundancy analysis (RDA) revealed that organic carbon and summer temperature were the predominant drivers of chironomid community turnover since 1880 in both lakes (Fig. 7A–D). The five variables selected for analysis were summer temperature, LOI_{550} (organic carbon), winter precipitation, spring precipitation and summer precipitation. NAO was excluded in the redundancy analysis as this phenomenon is a combination of numerous climate variables, and is a driver of seasonal temperature and precipitation rather than a direct local influence. Additionally, NAO showed no relationship to C-IT when plotted passively (Fig. 6A, B). DMAR was also not included, as more than half of the DMAR values are interpolated. Finally, autumn precipitation was excluded as there is no hypothesis-driven reason for its inclusion.

For Lough Meenagraun, LOI_{550} shows a strong relationship with RDA Axis 1 ($\lambda = 0.133$), while summer temperature is more strongly related to RDA Axis 2 ($\lambda = 0.110$). The RDA sample-environment bi-plot shows that samples post-1980 follow along the temperature vector (Fig. 7A). Furthermore, a synchronous and notable abrupt decline in organic carbon content and DMAR occurred in 1980 (Fig. 6A). The species-environment bi-plot also shows that *Heterotanytarsus,* which is associated with humic waters and closely related to LOI_{550} (Fig. 7B), drops in abundance at this time. This likely indicates that a reduction in the input of terrestrial peat material to the lake occurred after 1980, likely the result of decreased land disturbance from sheep grazing. This evidence implicates that a reduction in the intensity of human activities in the catchment took place post-1980, at a time when warming conditions began to establish, allowing summer temperature to be the strongest variable influencing the chironomid trajectory in recent years. Partial RDAs further illustrate that LOI_{550} and summer temperature are having the greatest influence on chironomid community change, explaining 11.6 and 8.4% of variance, respectively (Table 1). LOI_{550} became stronger once seasonal precipitation was factored out (14.4%), while summer temperature weakens slightly when any combination of variables is factored out. Although *P* values illustrate that summer temperature is not significant, it seems to have an influence on chironomid community over the recent past, especially after mid-1980 s, when samples steadily follow an increasing temperature trend.

For Lough Ballygawley, summer temperature displays the strongest relationship with Axis 1 ($\lambda = 0.161$), while LOI_{550} shows the strongest affiliation with Axis 2 ($\lambda = 0.055$). Samples on the right of Axis 1 (Fig. 7C) reveal warm conditions in the most recent section of the core from 1982 to 2009, while samples on the left of Axis 1 spanning 1885 to 1979 are dominated by taxa associated with agricultural activities and more productive lakes (Potito et al., 2014) (Fig. 7D). *Stempellina* is found in its highest abundance in samples spanning 1910–1929, in the upper left quartile of the species-environment bi-plot. This taxon is associated with oligotrophic lake conditions and is found in samples with lower LOI_{550} values. This could indicate that a fall in LOI_{550} is linked with a decrease in lake productivity. Partial RDAs indicate that summer temperature is the only significant variable, explaining 10.6% of the variance (Table 1). This variable exhibits high λ_1/λ_2 ratios due to its strong relationship to RDA Axis 1. Summer temperature became more significant once seasonal precipitation was partialled out (11.3%).

Discussion

Reconstructing temperature pathways in lake systems is complex (Jeppesen et al., 2014). This is particularly true in small shallow lakes, where climate can exaggerate the nutrient enrichment process, since heat and energy are more easily transferred within these lakes than in deeper systems (Dong et al., 2012). Furthermore, the interaction between local (nutrient enrichment) and extra-regional (climate) drivers may vary among different trophic states (Huber et al., 2008). In this study, both human pressures and climate change exerted a notable influence on the chironomid communities in two shallow lakes. Chironomid analysis has been employed in an attempt to reconstruct two unique lake histories and disentangle the climate and human impact signals. In the Irish training set, July temperature emerged as the most important control on chironomid distribution spanning a variety

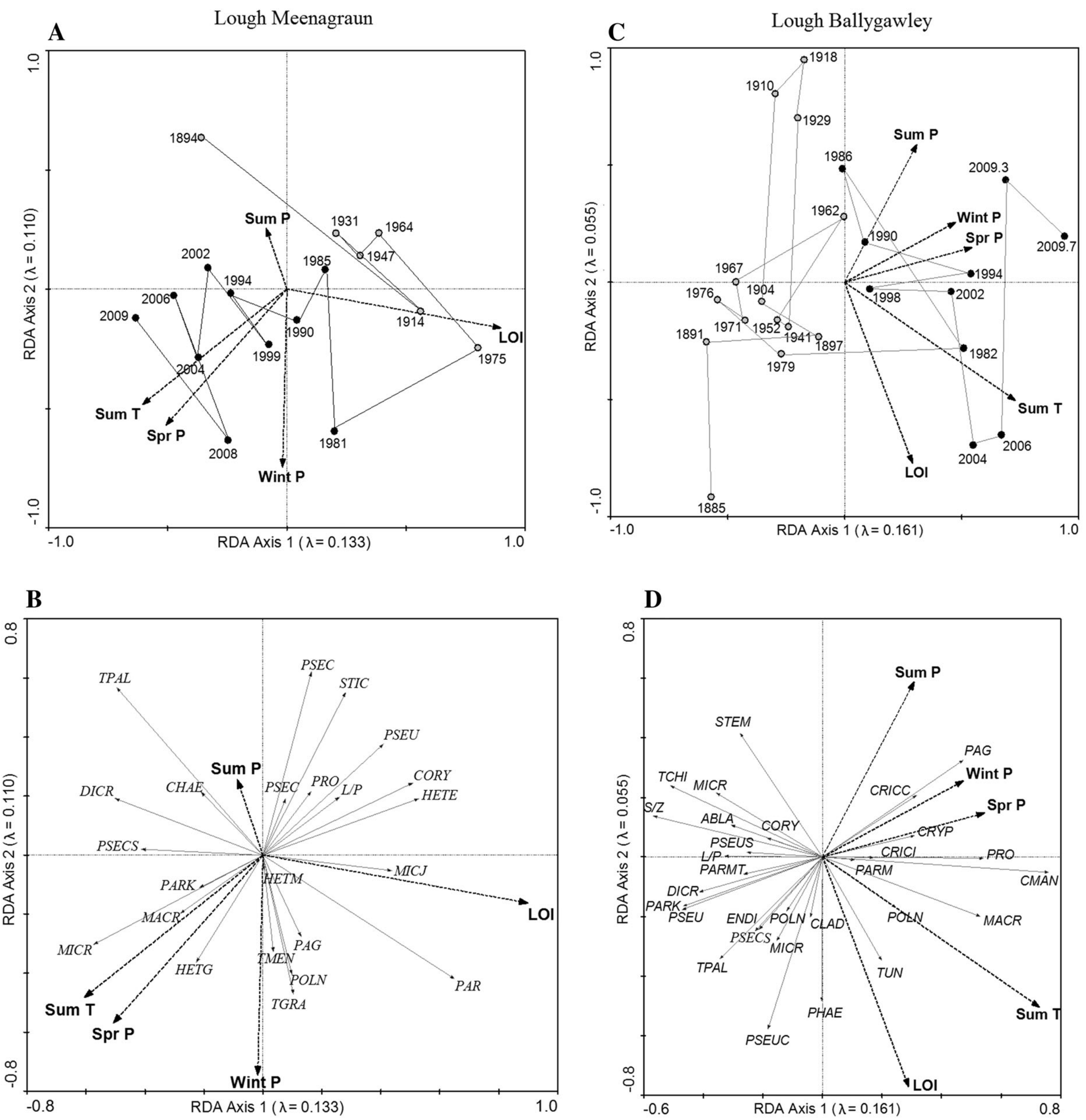


Fig. 7 RDA sample-environment and species-environment biplots for Lough Meenagraun (**A**, **B**) and Lough Ballygawley (**C**, **D**). Chironomid abbreviations in (**B**) and (**D**) are as follows: ABLA *Ablabesmyia*, CHAE *Chaetocladius*, CLAD *Cladopelma*, CORY *Corynoneura edwardsi*-type, CRICC *Cricotopus cylindraceus*-type, CRICI *Cricotopus intersectus*-type, CRYP *Cryptochironomus*, DICR *Dicrotendipes nervosus*-type, ENDI *Endochironomus impar*-type, HETE *Heterotanytarsus*, HETG *Heterotrissocladius grimshawi*-type, HETM *Heterotrissocladius marcidus*-type, L/P *Limnophyes/Paralimnophyes*, MACR *Macropelopia*, MICJ *Micropsectra junci-type*, MICR *Microtendipes pedellus*-type, PAG *Pagastiella*, PARK *Parakiefferiella bathophila*-type, PARM *Paramerina*, PARMT *Parametriocnemus*, PHAE *Phaenopsectra flavipes*-type, POLN *Polypedilum nubifer*-type, PRO *Procladius*, PSEC *Psectrocladius septentrionalis*-type, PSECC *Psectrocladius calcaratus*-type, PSECS *Psectrocladius sordidellus/psilopterus*-type, PSEUC *Pseudochironomus*, PSEUS *Pseudosmittia*, S/Z *Stempellinella/Zavrelia*, STEM *Stempellina*, STIC *Stictochironomus rosenschoeldi*-type, TCHI *Tanytarsus chinyensis*-type, TGRA *Tanytarsus gracilentus*-type, TUN *Tanytarsus* undefined, TMEN *Tanytarsus mendax*-type, TPAL *Tanytarsus pallidicornis*-type

Table 1 Partial RDAs for each environmental variable

Variable	Covariable	Lough Meenagraun				Lough Ballygawley			
		λ_1	λ_1/λ_2	P	% variance	λ_1	λ_1/λ_2	P	% variance
Sum T	None	0.084	0.477	0.138	8.4	0.106	0.589	0.004	10.6
	LOI	0.630	0.440	0.380	7.2	0.091	0.508	0.008	9.7
	Seasonal P	0.055	0.341	0.554	7.2	0.904	0.672	0.006	11.3
	LOI and seasonal P	0.040	0.350	0.756	6.1	0.073	0.545	0.032	9.4
LOI	None	0.116	0.670	0.014	11.6	0.056	0.244	0.190	5.6
	Sum T	0.096	0.671	0.052	10.5	0.041	0.229	0.414	4.6
	Seasonal P	0.111	0.895	0.012	14.4	0.060	0.395	0.122	7.2
	Sum T and seasonal P	0.096	0.842	0.030	13.5	0.039	0.291	0.466	5.2
Wint P	None	0.079	0.401	0.180	7.9	0.590	0.284	0.130	5.9
	Sum T	0.070	0.426	0.280	7.7	0.044	0.272	0.370	4.9
	LOI	0.085	0.578	0.072	9.6	0.065	0.344	0.076	6.9
	Spr P and Sum P	0.069	0.377	0.308	8.3	0.061	0.359	0.130	6.8
	Sum T, LOI, Spr P and Sum P	0.074	0.679	0.194	10.7	0.043	0.321	0.370	5.8
Spr P	None	0.082	0.443	0.178	8.2	0.064	0.315	0.088	6.4
	Sum T	0.053	0.301	0.658	5.8	0.062	0.431	0.068	6.9
	LOI	0.071	0.476	0.260	8.1	0.063	0.325	0.090	6.7
	Wint P and Sum P	0.072	0.393	0.284	8.6	0.046	0.271	0.362	5.2
	Sum T, LOI, Wint P and Sum P	0.049	0.429	0.624	7.4	0.044	0.328	0.354	5.9
Sum P	None	0.082	0.414	0.136	8.2	0.048	0.208	0.312	4.8
	Sum T	0.083	0.482	0.116	9.0	0.056	0.344	0.142	6.2
	LOI	0.081	0.487	0.088	9.2	0.048	0.220	0.310	5.1
	Wint P and Spr P	0.080	0.437	0.124	9.5	0.045	0.265	0.378	5.1
	Sum T, LOI, Wint P and Spr P	0.078	0.684	0.110	11.3	0.049	0.366	0.236	6.5

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

of lake types (Potito et al., 2014). Temperature tends to be the main driver in chironomid distribution through space and time (Eggermont and Heiri, 2012); however, the chironomid–temperature relationship can be decoupled by other confounding factors, such as nutrient inputs, and other nutrient-mediated factors such as macrophyte abundances and dissolved organic carbon. The effects of human activities at Lough Meenagraun and Lough Ballygawley were evident in both lake chronologies. However, temperature was also found to have a notable effect on both chironomid communities in the late twentieth century, albeit to varying degrees.

The influence of other climate/environmental variables, such as organic carbon (550°C) and dry mass accumulation rates (DMAR), Markree mean summer temperature (June, July and August), mean July air temperature, the warmest average July temperature for each sample interval, seasonal and annual precipitation and winter North Atlantic Oscillation (NAO) index values, were also assessed in order to further explore the dominant controls on the chironomid community through time. In Lough Ballygawley, summer temperature appeared to be the most important environmental variable, as a correspondence is evident with both the chironomid-inferred temperature data and the inverse values of PCA Axis 1. NAO and precipitation variables seem to have a weaker correspondence with chironomid community change through time for this lake. In Lough Meenagraun, organic carbon appears to be following chironomid PCA Axis 1 scores in the earliest portion of the stratigraphy from the late nineteenth century until the mid-1950 s, indicating that organic carbon is likely influencing the chironomid community in this section of the core. In the late twentieth century, mean July temperatures and anomalously warm years in the month of July (taking the warmest July month over the sample interval) followed the chironomid–temperature inferences model more closely than Markree mean summer temperatures (taking the average from each sample's interval). The difference between the two chironomid community responses to temperature change could be due to site-specific differences in lake productivity, lake morphology and water chemistry. Differences in inferred temperatures could also be due to the fact that temperature changes are within the prediction errors of the inference model (0.57°C). Despite the minor differences in C-IT models from Lough Meenagraun and Lough Ballygawley, an increase in warm water taxa is a key feature in the late twentieth century in both lakes.

The chironomid community from Lough Meenagraun proved to be more climatically sensitive than Lough Ballygawley post-1985, with chironomid-inferred temperatures (C-IT) generally following Markree instrumental summer temperature trends. This marks the period when summer warming became prominent in the Markree instrumental record (McKeown et al., 2012). Redundancy analysis provides further evidence of recent warming as samples post-1985 are loading positively along the Summer T vector. In these decades, the Lough Meenagraun C-IT is being driven towards warmer values due to the relatively high abundance of warm water taxa such as *P. nubifer*-type and the low abundance of cold stenotherms such as *Psectrocladius rosenschoeldi*-type and *Psectrocladius septentrionalis*-type. However, faunal turnover depicted in the Lough Ballygawley stratigraphy suggests a more a complex history. Recent community change appears to be related to a measure of temperature, where CI-T is increasing post-1970. This warming is largely driven by the increasing dominance of *C. mancus*-type, a warm stenotherm in the Irish training set (Potito et al., 2014). However, the RDA bi-plot highlights the complexity of the chironomid–temperature relationship, where the most recent shift in faunal turnover is loading negatively on the Summer T vector during the 1982–1986 interval, thus suggesting cooling instead of warming. This contradicts the warming presented in the C-IT and suggests that the chironomid–temperature relationship in Lough Ballygawley is not unambiguously attributed to changes in July temperature. Therefore, although partial RDAs indicate that summer temperature is the only significant variable explaining 10.6% of variance in the chironomid community, it is clear that the chironomid–temperature relationship does not follow a simple scheme. As nutrient conditions and trophic state co-vary with temperature, it can be difficult to distinguish chironomid community response to changes in one or both of these variables. Confusion can also occur as chironomid taxa characteristic of warm water lakes is also characteristic of productive, eutrophic waters, while cold water taxa are also associated with oligotrophic lake conditions (Brooks et al., 2001). In Ireland, human activities that strongly affect the nutrient loading can lead to abrupt shifts in chironomid communities (Garthorne-Hardy et al., 2009), and agriculture is the human activity that is largely responsible for nutrient loading in Irish lakes (Ulén et al., 2007). Our results suggest that the trophic levels of Lough Meenagraun and Lough Ballygawley notably altered after the cultural and agricultural changes that occurred as a result of the Great Irish Famine of 1845–1849, and throughout the twentieth century. Evidence derived from historical documents is concurrent with shifts in ecosystem equilibria inferred from the chironomid communities at both lakes. However, the two lakes present unique histories reflecting the different local land-use change at each of the study sites. Beyond the ^{210}Pb-dated section of the Lough Meenagraun core, there is an obvious regime shift in the chironomid community in the mid-nineteenth century. An increase in taxa associated with eutrophic lake conditions, such as *M. pedellus*-type, *T. pallidicornis*-type, *P. nubifer*-type and *C. edwardsi*-type, after 1850 supports documentary evidence of an intensification of sheep farming within the lake catchment. Excessive erosion associated with overgrazing sheep in highland areas can lead to degradation of waterbodies (Dalton et al., 2014), as the erosion of peats can lead to excess levels of suspended sediment (Mainstone et al., 2008) with major ecological impacts (Dalton et al., 2014). Furthermore, evidence of 'new' large boulders around one of the outlet channels also suggests that the lake level was managed in conjunction with the intensification of land-use. Focusing on specific taxa associated with terrestrial/semi-terrestrial environments, such as *Bryophaenocladius, Smittia, Limnophyes/*

Paralimnophyes and *Pseudosmittia*, it is suggested that an increase in these taxa can be linked to a rise in lake level and flooding of surrounding shelves. *Heterotanytarsus* also becomes more dominant post-1850, indicating that the input of peat material into the lake likely increased, creating humic water conditions in which this taxon is known to thrive (Cranston, 1982). The introduction or expansion of agricultural activities around the Lough Meenagraun catchment, and evident alterations in lake level, likely influenced the capacity of the system to cope with the environmental change and shifted the chironomid community to an alternative stable state. As this transition occurred before 1850, it likely did not affect chironomid-inferred temperature estimates from the upper portion of the core. Chironomid communities still register a temperature signal over the instrumental period, thus confirming that the inference models can adequately capture temperature at sites where human influences are low to moderate. Although LOI_{550} proved to be the most dominant environmental variable through the dated portion of the record, redundancy analysis showed that samples followed an increasing temperature trend post-1985.

In Lough Ballygawley, the most notable changes in the chironomid community correspond to (1) known human-induced disturbance events such as forest clearance and changes in lake hydrology (drainage) in the late nineteenth and early twentieth centuries, and (2) elevated nutrient input as a result of increased agricultural activity during the late twentieth century. Faunal turnover in the early portion of the core (pre-dated section) and throughout the twentieth century appears to be related to changes in nutrient conditions driven by agricultural activity. The transition from zone 1 to zone 2 is characterised by a shift from eutrophic lake conditions to more oligotrophic conditions. This is evidenced by the increase in *Stempellina* and *Tanytarsus chinyensis*-type, which are associated with oligotrophic waters, and a decrease in taxa associated with agricultural activities, namely *T. pallidicornis*-type, *Cladopelma*, *Procladius*, and *P. nubifer*-type (Potito et al., 2014). Alleviation of farming activities around 1850 is likely to have taken place as a result of the large-scale shift in agriculture intensity caused by the Great Irish Famine of 1845–1849 (Turner, 1996). This likely promoted a growth in the dominance of oligotrophic species and a decline in taxa associated with eutrophic lake conditions. A dominant trend in the chironomid data throughout the late nineteenth to early twentieth century is a gradual shift towards more productive lake conditions, with an increase in taxa associated with mesotrophic-to-eutrophic conditions, such as *T. pallidicornis*-type, *Cladopelma*, *Procladius*, and *P. nubifer*-type, and a fall in taxa linked with more oligotrophic lakes, such as *Stempellina* and *T. chinyensis*-type. This is likely due to increased agricultural activities taking place in the late nineteenth century, and throughout the early twentieth century, once socio-economic conditions improved after the Famine. In the late 1950 s, *Stempellina* declines in numbers throughout until the 1970 s, while *Stempellinella,* which is associated with mesotrophic lake states, becomes more abundant. This peak in *Stempellinella* corresponds with an increase in taxa associated with agricultural activities, namely *T. pallidicornis*-type, *Cladopelma*, *Parakiefferiella bathophila*-type, *Procladius*, and *P. nubifer*-type along with lower levels of *Cricotopus cylindraceus*-type, *C. edwardsi*-type, *Glyptotendipes pallens*-type, *Micropsectra junci*-type and *Endochironomus impar*-type. This corresponds with the introduction of a national-scale scheme that subsidised the cost of lime and phosphorus fertilisers for Irish farmers (Brogan et al., 2001). The use of fertilisers on agricultural land in the catchment of Lough Ballygawley in the mid-twentieth century is thus a likely cause of the shift to the more productive lake conditions evident in the chironomid stratigraphy.

The RDA bi-plot suggests a number of notable shifts through the record, namely between 1885 and 1891; 1904 and 1918; 1918 and 1941; and 1979 and 1982. The first two events are characterised by the chironomid community loading negatively on the LOI vector. Documentary evidence indicates that Lough Ballygawley was drained at both of these times, as specified in a document entitled 'The Lake dwellings of Ireland: or Ancient Lacustrine Habitations of Erin, Commonly Called Crannogs' (Woodmartin, 1886) and according to a report for the National Parks and Wildlife Service (Goodwillie et al., 1992). At this time, lakes were drained for the reclamation of land for agricultural activities. An increase in the numbers of *Limnophyes/Paralimnophyes,* associated with terrestrial/semi-terrestrial environments, and *Psectrocladius sordidellus/psilopterus*-type, linked with macrophytes, occurs on both occasions, particularly during the more recent drainage operation in the early twentieth century. This also coincided with a notable fall in organic content, adding further confidence for a change in hydrological conditions. The 1918–1941 shift potentially indicates an increase or intensification of agriculture around Lough Ballygawley as there is an increase in the number and diversity of taxa associated with productive lakes and agricultural activities is notable around this time, namely *T. pallidicornis*-type, *Cladopelma*, *Parakiefferiella* and *P. nubifer*-type. The 1979–1982 shift is more complex with an increase in warm water taxa such as *Cladotanytarsus* and *Pagastiella*, along with a slight increase in taxa associated with agricultural activities such as *Procladius*. The 1970 s and early 1980 s mark another period of increased nutrient loading likely from agricultural intensification. Finally, the expansion of forestry activities in the late 1940 s, 1960 s, 1990 s and 2000 s does not seem to have a significant impact on the chironomid community in the lake. Although the land cover in the catchment altered, it is not directly manifest in the chironomid record. This is potentially due to the buffering effect of deciduous trees along the lake, which likely protected the lake from direct impacts of deforestation and associated erosion. Despite these changes in catchment activities, lake nutrient status and lake level at Lough Ballygawley, the C-IT has been shown to follow similar patterns to the Markree summer temperature record. Summer temperature also displays the strongest relationship with RDA Axis 1, and partial RDAs indicate that summer temperature is an important control on the chironomid community through the dated portion of the record. Therefore, summer temperature remains a prominent influence on chironomid communities, even in relatively active catchments.

Conclusion

This study provides valuable information on the sensitivity of chironomids to various environmental and climatic drivers. The evidence provided here shows the potential for chironomids to be used as palaeotemperate indicators in future research, as well as a tool to differentiate human and climate impacts on Irish lakes across various timescales. Here, chironomid reconstructions were used along with independent climate data and historical land-use information to provide more knowledge on the degree, nature and speed of faunal turnover over the recent past in Irish lakes. The rich history of human interaction with the Irish landscape and the close association of climate with north Atlantic phenomena make Ireland an ideal location for chironomid-based palaeolimnological research, and ideal for modern studies of complex human–climate–lake interactions. Significant anthropogenic disturbances were identified in both lakes through time, particularly around 1850 following the Irish Famine and throughout the twentieth century in Lough Ballygawley. These disturbances correspond to known periods of changes in nutrient input resulting from agricultural activity, as well as known disturbance events such as changes in lake hydrology. The impacts of human activities were more important than climate change in the late nineteenth and early twentieth centuries, which could be due to the scale of activities or the type of anthropogenic pressure occurring at a time of very subtle climate change. Temperature appeared to be an important driver since the mid-1980 s, when human influences were less pronounced in both lake catchments, particularly the less impacted Lough Meenagraun. This also occurred at a time when warming accelerated in Ireland, allowing temperature to be one of the most important controls on faunal turnover in the late twentieth and early twenty-first centuries. As climate change impacts on fresh water systems are similar to eutrophication symptoms, the results from the study show that the combined effects are difficult to disentangle using chironomid analysis in moderately impacted lakes such as Lough Ballygawley. Consequently, appropriate site selection, as well as multi-proxy analysis to assess catchment-based human activity, is highly important for longer term chironomid-based Irish temperature reconstructions in Ireland.

The results from this study further verify the applicability of the Ireland-based chironomid-inference model for reconstructing subdued July air temperature changes through time using Irish lakes that have not experienced significant human influence. The narrow temperature range and associated small RMSEP, along with the presence of human activity in the lake catchments, allow the model greater applicability for reconstructing Ireland's summer temperature regimes (Potito et al., 2014). Thus, the potential to use this technique to reconstruct Holocene temperatures exists, particularly for a region where climate change over this period remains poorly understood. Careful interpretation is essential as humans have been a dominant force on the landscape since at least the Irish Neolithic, 6000 years ago. Therefore, the importance of differentiating the temperature and human impact signals is especially important in Ireland. It is recommended that future Holocene climate reconstructions using a chironomid-based approach should be accompanied by pollen analysis in order to determine the timing and magnitude of agricultural activity within the lake catchment.

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