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A Multi-Proxy Holocene Palaeoenvironmental Record of Climate Change and Prehistoric Human Activity from Lough Cullin, southeast Ireland

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Keywords:	Palaeoecology, Pollen Analysis, Chronology, Archaeology, Ireland, Human Impact, Climate
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	from the latter date to 815-685 cal. BC, and a brief but pronounced cessation at 690-535 cal. BC. Renewed woodland clearance and agriculture commenced until 415-250 cal. BC. From the latter date until cal. AD 390-540, the Late Iron Age/Early Medieval period, a phase of woodland recovery is attested, followed by renewed landscape disturbance and arable agriculture in particular, continuing to the close of the record at cal. AD 780-1035.

A Multi-Proxy Holocene Palaeoenvironmental Record of Climate Change and Prehistoric Human Activity from Lough Cullin, southeast Ireland.

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Abstract.

A multiproxy (pollen, microcharcoal, loss-on-ignition, magnetic susceptibility and geochemistry) sequence from Lough Cullin, southeast Ireland, supported by a high-resolution radiocarbon chronology, modelled using Bayesian approaches, provides a record of environmental change for much of the Holocene. Following the establishment of mixed deciduous woodland, climatic deterioration was likely responsible for pronounced vegetation change and erosion, *7615-6500 cal. BC* to *6245-5575 cal. BC*, evidence for the '8.2 Kyr' BP climate event. The so-called 'elm decline' is dated to *4220-3980 cal. BC* and whilst there are possible indications of an anthropogenic cause, clear evidence of woodland clearance with cereal pollen is recorded at *3900-3700 cal. BC, 3790-3580 cal. BC* and *3760-3650 cal. BC,* during a period of clearance and farming of *320-450 years* duration. A reduction in farming/settlement and woodland regeneration during the Middle Neolithic parallels the archaeological record, with low levels of activity during the Late Neolithic/Chalcolithic after *2960-2525 cal. BC,* prior to increases during the Bronze Age then woodland clearance and agriculture between *1500-1410* and *1275-1000 cal. BC*, corresponding with the archaeological evidence. A subsequent 'step-wise' reduction in human activity follows, from the latter date to *815-685 cal. BC,* and a brief but pronounced cessation at *690-535 cal. BC. R*enewed woodland clearance and agriculture commenced until *415-250 cal. BC*. From the latter date until *cal. AD 390-540,* the Late Iron Age/Early Medieval period, a phase of woodland recovery is attested, followed by renewed landscape disturbance and arable agriculture in particular, continuing to the close of the record at *cal. AD 780-1035*.

Keywords: Palaeoecology, Pollen Analysis, Chronology, Archaeology, Ireland.

1. Introduction

Understanding the character and chronology of Holocene vegetation development and the respective roles of climatic and anthropogenic impact on patterns and process of landscape change is a key focus of palaeoecological research. There is a long history of such research in Ireland, where the wide distribution of peatland and lake deposits provides the required sampling sites, and investigations continue to provide new insights into environmental change. Various questions concern the timing and character of human activity, climatic change and its relationship to archaeology, continue to be a subject of ongoing debate (see Kelly and O'Carragain 2021 for a summary). A particular methodological issue concerns the production of tightly constrained chronologies that are now available for the archaeological record (Cooney *et al.* 2011; McClatchie *et al.* 2014; McLaughlin *et al.* 2016) and the utility of formal modelling procedures to generate robust estimates of the tempo of environmental changes such as those around the mid-Holocene ‘elm decline’ (e.g. Whitehouse *et al.* 2014; Kearney and Gearey, 2020) and the Bronze Age to Iron Age transition (e.g. Gearey *et al*., 2021). Whilst it has long been largely common practice to use 'single point' estimates to describe palaeoenvironmental chronologies, largely for reasons of perceived clarity of data presentation, we utilise posterior density estimates, as these reflect the inherent probabilistic uncertainty associated with radiocarbon dates. It is now usual in much archaeological research to present chronological information in this way (Whittle *et al.* 2011). In order to allow meaningful, robust comparisons between archaeological and palaeoenvironmental datasets, it is essential we standardise chronological 'currencies' and hence develop a 'best practice' approach.

Recent detailed palaeoenvironmental studies have focussed on the west and north of the island (e.g Chique *et al.* 2017; Spencer *et al.* 2020; Stolze and Monecke 2020) but there has been relatively little research in the southeast (see Eogan *et al.* 2015). In this paper, we describe and discuss the results of a multi-proxy palaeoenvironmental analysis of a 7.75m core from Lough Cullin, Co. Kilkenny, southeast Ireland, which is supported by a high-resolution radiocarbon chronology. Compilation of archaeological evidence from the close vicinity of the sampling site provides an independent record of the relative intensity of human activity through time.

2. Background

Lough Cullin (52° 19’ N, -7° 06’ W). is a small lake (*c.*5 hectares) located in the catchment of the river Suir, in the south of County Kilkenny, southeast Ireland. The lake is situated in a low-lying landscape (11m OD), has a maximum depth of 3.4m and is fed by a series of small streams from the north (with a stream flowing through a channel incised into the Lower Palaeozoic and Devonian rocks at Catsrock), east and south. The outflow is via a small stream to the south-west. The lake is nestled in the centre of a syncline, with the underlying geology of the lake itself being well-bedded pale grey lower Dinantian limestones of the Ballysteen Formation (Tietzsch-Tyler and Sleeman 1994, the Hook Head formation of Keeley 1983). The slope increases significantly 2.5 km to the east and north of the lake basin, as the geology changes from limestone to Devonian sandstones. The recession of the lake due to nineteenth century drainage can be seen on the various editions of Ordnance Survey maps produced during the nineteenth and early twentieth centuries. John O'Donovan, who was one of the civilians employed by the Ordnance Survey of Ireland in the 1830s and compiled the name books for the Ordnance Survey, remarked: 'I remember this lake when it was of considerable extent. It is now nearly drained, and the bog nearly all cut out' (OSI, n.d.). There is also sedimentological evidence the lake was once larger, with lacustrine sediments filling an area of 2 km^2 around the lake. The presence of a glaciofluvial sand and gravel deposit to the north of the lake between it and the channel at Catsrock, suggests the lake may, partly at least, owe its origin to glacial meltwater.

3. Methods and Materials

3.1. Core sampling and lithostratigraphy.

In June 2012, a 7.75 metre sediment core was extracted from the deepest part of the lake using a Livingstone piston corer from a platform secured in the centre of the lake. The core was extracted and wrapped on site, and later transferred to the lab where it was cut in half along its length. One half was used for geochemical analysis, and both halves were subsampled at 1 cm intervals down to 6.33 metres (the top of the clays).

3.2. Palynological analysis

Sub-samples of 1 cm^3 were prepared for pollen analyses following standard techniques including KOH digestion, HF treatment and acetylation (Moore *et al.*, 1991). Pollen concentrations were established by adding a known concentration of *Lycopodium clavatum* spore (batch number 177745) to the samples before treatment (Stockmarr 1971). Pollen counts were made using a Leica DM 1000 LED microscope at x400, x800 and x1000 magnification under oil immersion for critical examination of pollen sculpture and measurement of pollen grains. A minimum pollen sum of 400 Total Land Pollen (TLP) grains, excluding spores and aquatics, was employed. Pollen grains were identified mainly using the key from Moore *et al.* (1991) and Bennett (1995), with reference to Fægri *et al.* (1989). Pollen and spore identification was made to the lowest taxonomic level possible using the available references and following the nomenclature of Stace (1997), with suggestions from Bennett *et al.* (1994). The programmes TILIA and TILIA - GRAPH (Grimm 2013) were used to construct spreadsheets and pollen diagrams. Local pollen assemblage zones (LPAZ) were defined based on visible changes in the pollen record.

3.3. Loss on Ignition (LoI)

Sediment samples (*c.*5 cm^3) were taken at 2 cm intervals to calculate loss-on-ignition (LoI %). The samples were dried for 24 hours at 105˚C and subsequently transferred to porcelain crucibles and ashed for 4 hours at 550 ˚C (after Bengtsson and Enell, 1986; Heiri *et al.*, 2001).

3.4. Geochemical analysis

Geochemical analysis was carried out through non-destructive X-ray fluorescence (XRF) core scanning of the split cores using a Cox Analytical Systems ITRAX XRF Core Scanner located in the School of Geography, University College Dublin. 28 trace elements were selected for analysis (Mg, Al, Si, P, S, Cl, Ar, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ge, As, Br, Rb, Sr, Y, Zr, Ba, Nd, Pb, U), of which 10 key elements (Fe, Si, Ti, Ca, K, Sr, Rb, Mn, Cu, and Br) and the ratio of inc:coh were chosen for interpretation. Cores were scanned at 600 µm step intervals with a count time of 15 seconds, using a Mo tube operating at 30 kV and 30 mA.

The elemental data obtained are counts only, and so should be considered as semi-quantitative in nature (Croudace *et al.* 2006; Weltje and Tjallingii 2008). The data was normalized using kilo counts per second (kcps) to account for the variation in XRF intensities (Jouve *et al.* 2013; Turner *et al.* 2015; Gregory *et al.* 2019). Relative elemental concentrations within a core can provide valuable information on the sedimentology and palaeoclimatic history of an area (Guyard *et al.* 2007), particularly when coupled with data from other methodologies.

Along with the geochemical data, the ITRAX scanner returns a profile of the magnetic susceptibility (MS) measurement of the core at 4 mm resolution. MS is the amount of magnetisation acquired by the sediments of the core due to the application of a weak magnetic field. MS is related to the amount of dia- para- and ferrimagnetic minerals within the core (Støren *et al.* 2016), and changes in MS can be indicative of sediment flux and erosion in lake catchments (Evans and Slaymaker 2004).

3.5. Chronology

3.5.1. Radiocarbon Dating

Thirty-three samples (52 measurements in total) were dated by Accelerator Mass Spectrometry at the Scottish Universities Environmental Research Centre (SUERC-), Queen's University Belfast (UBA-) and Beta Analytic (Beta-). All measurements were obtained from organic sediment samples except for *UBA-22422*, which was obtained from a branch fragment of *Salix* sp. (willow). Where possible, duplicate measurements on the humin (the acid and alkali-insoluble) and humic (alkali-soluble, acid insoluble) fractions (Cook *et al.* 1998, 21) were obtained to test the reliability of sediment derived radiocarbon determinations (cf. Brock *et al.* 2011) and the statistical consistency (Ward and Wilson 1978) of each paired date assessed using the OxCal (Bronk Ramsey 2009a) programme.

The resulting radiocarbon determinations are presented as conventional radiocarbon ages (Stuiver and Polach 1977) quoted in accordance with the international standard established by the Trondheim Convention (Stuiver and Kra 1986). The calibrations have been calculated using the published datasets, IntCal20, (Reimer *et al.* 2020) and the computer program OxCal v4.3 (Bronk Ramsey 2009a) and are cited with the end points rounded outward to 10 years. The calibrated date ranges have been calculated using the maximum intercept method (Stuiver and Reimer 1986) and the graphical distribution of the calibrated result derived from the probability method (Stuiver and Reimer 1993). All radiocarbon dates are cited at 95.4% confidence, unless stated otherwise.

3.5.2. Bayesian Modelling.

In order to refine the chronology of palynological features and extend the chronological framework to changes which fall between dated horizons, a Bayesian approach was employed to the modelling of the radiocarbon dates (Buck *et al.* 1992). The Bayesian approach has been widely discussed in the literature (e.g. Blaauw and Christensen 2005; Blaauw *et al.* 2007a; Blaauw *et al.* 2007b; Bronk Ramsey 2008). The approach taken here uses the software OxCal v4.3 program (Bronk Ramsey 2009a), and the *P_Sequence* function (Bronk Ramsey 2008) was chosen to allow for a Poisson process, or a potentially random rate, of sediment formation. The prior information for the deposition rate was defined as log_10(*k*/*k*_0) where k_0 = 1. This allows *k* to take any value from 0.01–100. This value used was estimated from the radiocarbon dates following the approach outlined in Blockley *et al.* (2007; 2008)

The command *Outlier()* was used in OxCal (Bronk Ramsey 2009b) to identify any measurements that were statistically defined as outliers at a 0.05 probability (1 in 20 chance). The model has been constrained using *Boundaries*, the depths of which have been defined based on stratigraphic changes (see below). The ranges quoted in italics are *posterior density estimates*, derived from this Bayesian modelling of the radiocarbon chronology (Bayliss *et al.* 2007) and are cited at 95.4% probability, unless stated otherwise.

4. Results.

4.1. Stratigraphy.

The core lithology was (from top to bottom) light grey, organic-rich sediment (0 - 1.75 m); dark brown gyttja (1.75 m - 6.26 m), with a layer of sandier gyttja between 5.55 m and 5.74 m. The gyttja lies above 6 cm of sand (6.26 m - 6.32 m). At the base of the sequence was 1.65 metres of laminated grey-brown silty clay, with an angular pebble within the sediment at 7 metres.

4.2. Palynological analysis.

A total of forty-nine different taxa, including spores, were recorded across the Lough Cullin pollen profile. The data is presented in Table 1 and the percentage pollen diagram LC (Figure 2) and pollen concentration diagram (Figure 3) have been divided in 13 local pollen assemblage zones (LPAZ). LPAZ boundaries are given as *posterior density estimates* derived from the age-depth model shown in Figure 5. In addition, a curve for 'anthropogenic indicator' (*sensu* Behre 1981) taxa has been calculated (comprising *Cerealia*-type, *Artemisia*-type, Asteraceae undif., Caryophyllaceae, *Plantago lanceolata, Plantago major/media, Rumex, Trifolium*-type, and *Urtica dioica*).

4.3. Loss on Ignition (LoI), Magnetic Susceptibility (MS) and Geochemistry

The results of loss on ignition are presented in Table 1 and, with the results of geochemistry and magnetic susceptibility analyses, shown in Figure 4. Zonation for LoI data follows the LPAZ used in the pollen diagram. LoI results are relatively stable throughout the sequence, with some generally minor fluctuations. However, there is a marked decrease in LoI values at 5.09 m, with a significant and more sudden decrease at 4.90 m, possibly indicating accelerated minerogenic sedimentation into the lake. LoI begins to increase at 3.14 m to a peak at 2.15 m, from where it decreases to the top of the core.

The geochemical data, given the high resolution, is 'noisy' and must be interpreted with some caution. These data do not always track the changes in LoI, but there are observable patterns which may be hypothesised as reflecting weathering and erosion of different areas of the catchment: in particular, increased values for Calcium (Ca) may derive predominantly from the limestone bedrock areas (see above, Section 2), with Iron (Fe) from the sandstone areas. The latter element does not consistently track the MS curve, possibly because of the dissolution of magnetic minerals.

4.4. Chronology

4.4.1. Radiocarbon dating and Bayesian modelling.

The measurement on the humic fraction GU43402 from 2.61m failed, therefore the humin measurement (SUERC-72571) from this depth was used in the model. Four pairs of measurements from 2.65m (SUERC-70823 and SUERC-70824), 2.71m (SUERC-70825 and SUERC-70826), 3.26m (SUERC-76326 and SUERC-76666) and 5.34m (SUERC-70843 and SUERC-70844) are not statistically consistent (see Table 2). In all instances the humic fraction is younger than the humin fraction; this is likely caused by the downwards penetration of humic acids from above, therefore the humin fractions (SUERC-70824, SUERC-70826, SUERC-76666 and SUERC-70844) have been used in the modelling process for these depths. Measurement UBA-22422, a fragment of *Salix* (willow) twig, was identified as a possible outlier and has been excluded from the model; this determination was considerably older than those below it, suggesting that reworked material had been incorporated into the profile.

An age-depth model (Bronk Ramsey 2008) for the profile was constructed to provide a chronology for the sequence. The *P_Sequence* model (Figure 5) has good agreement (A_{model}=99) and has been used to provide estimates for the boundaries between the local pollen assemblage zones (Table 1). Except for UBA-22422 (the *Salix* twig) the model shows good agreement, suggesting the sequence is intact below 2.19m.

The pollen sequence can be estimated to cover a period of *8830-9560 years* (*95.4% probability*, distribution not shown), probably *9060-9330 years* (*68.2% probability,* distribution not shown). Estimates derived from the age-depth model suggest an average deposition rate of *4-5 cm/100yr* (distribution not shown) between the upper and basal radiocarbon measurements; it can be estimated that *21-23 years* (distribution not shown) are represented in every centimetre.

The effectiveness of the model can be seen by considering the radiocarbon determination UBA-22423: this provided a calibrated (unmodelled) date of 750-400 cal. BC. The output on the model (Figure 5) constrained this to *595-445 cal. BC* (Figure 5), a significant reduction in the bandwidth, from 350 to 150 years. This reduction was partly achieved through obtaining two determinations that fell on the 'steep' part of the radiocarbon calibration curve (SUERC-70824 and Beta-426775) thus helping to constrain the determinations between them, in particular those on the 'Hallstatt plateau'.

5. Interpretation

LC-1: 6.25-6.03m*, 9050-8090 cal. BC* to *7615-6500 cal. BC*

The pollen diagram covers much of the Holocene from *9030-8065 cal. BC* to *cal. AD 780-1035,* the Early Mesolithic to the Medieval period. *Quercus* (oak) and *Ulmus* (elm) are well established from the base of the sequence and constitute the main tall canopy trees in the landscape around Lough Cullin. *Corylus avellana*-type (probably largely hazel) is abundant, comprising a major component of the vegetation, probably as an under-storey shrub, while *Betula* (birch) and *Salix* (willow) had minor presences in the landscape. Low values for non-arboreal pollen (NAP),<5%, suggest the woodland had a rather closed structure. The presence of *Hedera helix* (ivy) and *Polypodium vulgare* (common polypody) probably indicate the presence of epiphytes (Molloy and O'Connell 1991).

LC-2: 6.03-5.88m, *7615-6500 cal. BC* to *6245-5575 cal. BC*

Zone LC-2 is marked by a decrease in hazel (*c.*50% to 30%) and oak (*c.*30% to 20%) and corresponding increases in *Pinus sylvestris* (Scots' pine) (*c.*4% to 20%) and birch (*c.*4% to 15%) between 5.97 to 5.93m. Hazel falls to its lowest value for the zone at 5.89m, corresponding to a peak in birch; whilst oak reaches its lowest percentage at 5.93m, at which point pine demonstrates a clear peak, attaining its highest values for the entire sequence before falling again. There are also reductions in elm and ivy apparent across these levels. Total NAP values do not show any fluctuations, suggesting the vegetation changes involved the woodland canopy taxa. Total pollen concentrations display a marked reduction across these levels, from $232x10^3$ to $155x10^3$ grains cm^{-3}, which may reflect fluctuations in relative pollen productivity.

In terms of geochemistry, this zone sees the highest values for Ti, Ca and Mn for the entire diagram, tracking increasing values for MS, although LoI percentages remain fairly steady (*c.*30%). This pattern may indicate a change in the source of inorganic material eroded from the catchment, with weathering of the soils on the limestone (Ca) as well as the sandstone bedrock (Fe) implied. These fluctuations are closely associated with the changes in woodland composition outlined above. Taken collectively, the data may well indicate the impact of climatic deterioration, with destabilised soils across the catchment associated with pronounced declines in thermophilous arboreal taxa (oak, hazel, elm and ivy), and related expansion in trees/shrubs (pine and birch) tolerant of colder conditions.

Towards the top of LC-2, *Alnus glutinosa* (alder) percentages begin to rise, implying the establishment of this tree, probably as alder carr at the lake edge. The date for the establishment of alder (5.89m, *6350-5910 cal. BC*, the 'rational limit', *sensu* Smith and Pilcher 1978) appears to be slightly earlier than elsewhere across Ireland. This spread and expansion of alder post-7000 BP appears to have been erratic in space and time (Bennett and Birks 1990): for example, alder became established after 5490-5010 cal. BC (6315±110, *D-115*) at Belle Lake (Craig 1978), after 5480-5070 cal. BC (6330±80, *Beta-65095*) at Clara Bog (Connolly 1999; Crushell *et al.* 2008), whilst at Lough Kinale (Ballywillin Crannog core) this tree expanded after 5720-5560 cal. BC (6720±40, *Beta-173320*; Brown *et al.* 2005; Selby *et al.* 2005).

LC-3: 5.88-5.19m, *6245-5575 cal. BC* to *4320-4020 cal. BC*

By the close of LC-2, oak and hazel recovered as the dominant woodland taxa. Arboreal taxa remain very well represented in LC-3 (minimum 95%) with few other marked changes. However, *Ilex aquifolium* (holly) is recorded from midway through the zone (5.30m): this shrub tends to become established in more open conditions (Molloy and O'Connell 1987), but there is no evidence of significant changes to the woodland structure that might suggest disturbance similar to the previous zone. Indicators of open environments such as *Plantago lanceolata* (ribwort plantain), are present only sporadically prior to the establishment of holly, but cease during the initial expansion of the latter. The low levels of NAP (<5%) suggest open environments were limited, although the extent of openness will have been greater than implied by the percentages.

The LoI values do not show any marked changes, falling slightly towards the top of the zone. The geochemical data show reductions for Ca and Mn, although there are increases in Mn midway through the zone. Fluctuating values for Fe with pronounced decreases at the top and base of the zone are apparent. These fluctuations are slightly enigmatic but might imply some destablisation of the local soils, albeit not on a similar scale to LC-2.

LC-4a: 5.90-5.01m, *4320-4020 cal. BC* to *4050-3960 cal. BC*

Zone LC-4a is defined by a pronounced reduction in elm from *4220-3980 cal. BC*, accompanied by a temporary fall in hazel, although other arboreal taxa remain steady. NAP increases (*c.*10%), primarily Poaceae (grass), but with sporadic grains of other herbs including ribwort plantain, Asteraceae (daisies) and Caryophyllaceae (pink family). There are decreases in LoI percentages across the zone coincident with increasing anthropogenic indicators, indicating increased mineral inwash into the lake and/or changes in accumulation rates associated with the reduction in woodland and expansion of open environments. This is supported by the rather abrupt fluctuations in Ti, Fe and Ca, indicating weathering and erosion in the lake catchment, again potentially involving soils on both the limestone and sandstone geologies.

LC-4b: 5.01-4.82m*, 4050-3960 cal. BC* to *3860-3650 cal. BC* and LC4c: 4.82-4.71m, *3860-3650 cal. BC* to *3685-3530 cal. BC*

Further reductions in arboreal pollen (AP), *c.* 80%, specifically oak and hazel are recorded from *4040-3910 cal. BC*, with rises in NAP (*c.* 20%) and a greater diversity of ruderal herbaceous taxa including ribwort plantain, Ranunculaceae (buttercups), *Rumex* (docks), daisies, *Artemisia*-type (mugwort) and *Urtica dioica* (nettles). This indicates the expansion of open, pastoral environments, at the expense of deciduous woodland, especially oak but with hazel affected to a lesser degree. The identification of *Cerealia*-type (cereal) grains at: *3890-3700 cal. BC, 3790-3580 cal. BC* and *3760-3560 cal. BC* demonstrate arable farming in the pollen catchment. The LoI percentages show an abrupt drop to their lowest values for the entire sequence (4.90m) corresponding to a peak in total anthropogenic indicators, followed by an equally abrupt recovery, indicating inwash of minerogenic material. There are no clear corresponding changes in the geochemistry, other than some fluctuations in Ti, nor does the MS show any response.

This phase lasted until *3860-3650 cal. BC***,** at which point AP began to recover (LC-4c). However, although there are reductions in NAP across this subzone, anthropogenic indicators including ribwort plantain and cereal-type are still recorded. The impression is of clearance of woodland and some destabilisation of soils during LC-4b, followed by a less intense period of human activity with some recovery of trees and shrubs in LC-4c. The initial phase lasted for

70-320 years, and the subsequent phase *10-270 years,* with the pollen data implying both pastoral and arable land-use.

LC-5: 4.71-4.35m*, 3685-3530 cal. BC* to *3355-3120 cal. BC* and LC-6; 4.38-4.08m, *3355-3120 cal. BC* to *2960-2525 cal. BC*

The overall AP values increase, especially elm, and the ribwort plantain curve is interrupted, reflecting woodland recovery. Elm populations regenerated, although not to their previous extent, while *Fraxinus* (ash) played an increased role in the arboreal vegetation dynamics, presumably expanding into the gaps created in the woodland in LC-4. This recovery of elm and associated woodland regeneration was sustained until *3310-3090 cal. BC*, when a second reduction in elm is apparent, primarily concomitant with increased representation of alder, a slight increase in ash and marginally increased levels of NAP, primarily in wet-loving taxa such as Cyperaceae (sedges) and *Filipendula* (meadowsweet). This suggests the expansion of wetland environments, probably in the form of alder carr at the lake's edge, perhaps as processes of hydroseral succession created favourable habitats. The muted response in NAP aside from the wetland taxa, raises questions concerning the cause and process of the decline in elm (see below). LoI values are stable (*c*.36%) across LC-5 and LC-6 but decline towards the top of the latter zone (*c*.30%). Some fluctuations in Fe are recorded, possibly indicating changes in the source of the minerogenic input into the lake.

LC-7a: 4.08-3.90m, *2960-2525 cal. BC* to *2620-2240 cal. BC*

A small but pronounced reduction in AP and re-establishment of a continuous curve for ribwort plantain and other light demanding ruderal/grassland taxa (including buttercups, daisies, mugwort, Lactuceae (dandelions etc.) are apparent from *2960-2525 cal. BC*, indicating an expansion of open, meadow environments. The woodland regeneration phase in the previous zones (LC-5 and 6) lasted between *660-1120 years*. The appearance of cereal-type pollen at *2860-2420 cal. BC* suggests arable farming around Lough Cullin. After the latter date, NAP continues to increase at the expense of primarily hazel and oak. Charcoal shows a slight increase and loss on ignition values are generally stable (*c*.30-34%); MS values increase coincident with a spike in Fe at *c*.4m, the highest values for anthropogenic indicators for this zone. These data collectively indicate catchment scale disturbance, related to the evidence for woodland reduction and the expansion of open environments.

LC-7b: 3.90-3.56m, *2620-2240* to *1880-1740 cal. BC* and LC-7c: 3.56-3.34m, *1880-1740* to *1500-1410 cal. BC*

Zone LC-7b is primarily defined on the basis of steadily increasing NAP, primarily grasses, with continuing low values of other herbs, suggesting open areas persisted but were of limited extent. Low values of microcharcoal are recorded, indicating restricted burning during this zone. This picture changes at the transition from LC-7b to LC-7c, around the Middle Bronze Age (*1880-1740 cal. BC*), with increases in ribwort plantain and the appearance of other anthropogenic indicators including dandelions and docks towards the close of the zone, reflecting an expansion in open, pastoral environments. However, percentages of arboreal pollen remain relatively steady, although there are fluctuations in hazel values. Charcoal values do not increase. The overall impression is of some expansion in open grassland environments, but only small decreases in woodland cover. The LoI values are largely stable, rising slightly across 7b (from *c.* 30 to 40%) before falling slightly across 7c. There are no clear changes in the MS or geochemical data other than a rise in Ca, possibly indicating disturbance on the limestone areas.

LC-8: 3.34-3.14m, *1500-1410* to *1275-1000 cal. BC*

The opening of LC-8 marks the beginning of a period of intensive human impact on the environment, the most pronounced recorded for the entire sequence. This seems to follow a brief period of reduced impact at the opening of the zone with reduced total anthropogenic indicators and increases in hazel, followed by a very pronounced increase in NAP (*c.* 45%), especially grasses, and associated decline in AP demonstrating a significant opening up of the woodland cover. The rising values for ribwort plantain (peaking *c.*7%) alongside grasses and to a lesser extent sedges, demonstrate the expansion of open, pastoral environments to form the greater proportion of the landscape around the lake. The occurrence of a single grain of cereal-type pollen at 3.20m (*1380-1220 cal. BC*) indicates arable farming. There are also reductions in alder, suggesting the alder carr on the wetter soils, probably close to the lake edges, were affected by clearance at this time.

However, a relatively restricted range of herbs is recorded: Chenopodiaceae (fat fen family), buttercups and *Succisa* (devil's bit scabious) appear alongside the peak of ribwort plantain, all of which are typical of open grassland/meadow environments. The concomitant increase in *Pteridium aquilinum* (bracken) across this zone is further evidence for the opening up of the landscape on drier soils, whilst a spike in charcoal demonstrates increased burning. The LoI percentages fall, generally tracking the increase in NAP, whilst in the geochemical data, Fe also shows pronounced peaks at the opening and close of the zone, coincident with small rises in Mn and Ti, and increases in the MS curves.

The combined data seem to indicate a short episode of reduced human activity and the recovery of shrubs, prior to intensive clearance and farming leading to soil disturbance across the catchment. Overall, the period between *1500-1410* and *1275-1000 cal. BC* was one of woodland reduction. Most parts of the landscape were affected, from the fertile dryland soils through to the 'marginal' wetland contexts. There is evidence for farming, predominantly of a pastoral character, and since cultivation is significantly underrepresented palynologically, arable plots were also present locally.

LC-9: 3.14-2.925m, *1275-1000 cal. BC* to *815-685 cal. BC* and LC-10: 2.925-2.82m, *815-685 cal. BC* to *690-535 cal. BC*

The previous period of woodland clearance and farming was followed by the recovery of woodland taxa (50-60%), especially hazel, oak and alder, accompanied by reductions in grasses and ribwort plantain (LC-9).However, increased diversity in herbs is recorded, specifically the anthropogenic indicators fat hen family, nettles and dandelions. Micro-charcoal values also increase, whilst a single cereal grain coincides with the peak in ribwort plantain at *1020-915 cal. BC* indicating the presence of arable and pastoral habitats.

However, the subsequent zone, LC-10**,** is notable for a marked fall in ribwort plantain and recovery of AP, especially hazel and oak, but with elm values also forming a low but consistent curve for much of the zone. Elm tends to thrive on fertile, better- drained soils that are often suitable for arable agriculture (as observed in the previous zones), implying that trees and shrubs re-colonised much of the landscape. The almost complete absence of microcharcoal also contributes to the impression of little anthropogenic activity, until the close of the zone. There is a small but sustained increase in LoI across the zone, with Fe values reduced relative to the previous zone, suggesting some stabilisation of the catchment soils related to the recovery of the woodland.

LC-11: 2.82-2.64m, *690-535 cal. BC* to *415-250 cal. BC* and LC-12: 2.64-2.36m, *415-250 cal. BC* to *390-540 cal. AD*

The landscape changed again at the opening of LC-11, with a fairly abrupt increase in ribwort plantain defining the zone transition, suggesting opening of the landscape. The response from other herbs, grasses included, is slightly muted, although levels of dandelions rise towards the close of the zone and there are occasional records of other grains such as mugwort, fat hen family, meadowsweet and buttercups. There is a steady reduction in hazel across the zone and oak also displays a fall, following a peak at the opening of the zone, contributing to falling AP from *c.*90% to 70% across the zone. Total anthropogenic indicators reach their highest percentage at the top of LC-11, at which point cereal-type pollen is recorded at *430-360 cal. BC*. However, microcharcoal values show only modest increases. The record therefore indicates a resurgence in human activity, which led initially to an expansion in grassland and pasture and the clearance of areas of woodland, with evidence for arable cultivation towards the end of the zone.

Almost immediately following the peak in pastoral and arable farming, there is evidence for what can only be described, on the basis of the pollen record, as the apparent possibly complete cessation of human activity. This is manifested through an abrupt drop in ribwort plantain at the opening of LC-12, and the disappearance of this species for the entire zone. Grasses also display a slight reduction, whilst few other herbs are recorded. Microcharcoal values are minimal and absent from the middle section of the zone, closely paralleling the behaviour of total anthropogenic indicators. AP percentages increase, mainly hazel and oak, but with some recovery in elm and birch. Overall, from around *415-250 cal. BC* to *390-540 cal. AD*, woodland dominated the landscape around Lough Cullin.

LC-13: 2.36-2.15m, *cal. AD 390-540* to *cal. AD 780-1035*

The final zone, LC-13, opens with the relatively abrupt resumption of the ribwort plantain curve, a steady rise in grasses and reductions in hazel and subsequently oak. Elm effectively disappears from the record and microcharcoal values also increase. Other herbs reappear including docks, mugworts and daisies etc., all of which form continuous curves. Total anthropogenic indicators demonstrate a marked increase whilst cereal-type pollen is recorded in almost all levels, indicating a significant expansion and persistence of arable cultivation in the pollen source area. Despite this, the maintenance of AP (*c.*80%) until the close of the diagram, suggests sizable areas of woodland remained locally. The diagram closes at *cal. AD 780-1035* with an indication of renewed falls in arboreal taxa suggesting further anthropogenic pressure on the woodland. There is a hint that by this time, clearance of woodland was starting to impact all parts of the landscape again, with alder falling to its lowest values since LPAZ LC-2 . The LoI values increase across the zone, with the rising values for Fe that began in LC-12 also continuing.

6. Discussion

Overview

The Lough Cullin sequence provides a record of vegetation change from the Early Mesolithic (*9050-8090 cal. BC*) through to the Medieval period (*cal. AD 780-1035*), a period of *10020-9025 years*. A series of phases of expansions and contractions of AP and NAP are apparent: with one exception (see below), these appear to reflect human disturbance, characterized by increases in taxa indicative of open, pastoral environments and disturbed soils (especially ribwort plantain, grasses, docks, dandelions and occasional grains of cereal pollen suggesting arable agriculture) and falls in values of tree/shrub pollen showing contraction in wood/scrubland.

It should be noted total tree and shrub pollen percentages rarely drop below 75% of total land pollen for the entire record, implying that although herbaceous taxa are probably underrepresented palynologically (Caseldine and Fyfe 2006), wood/scrub cover remained of greater extent than open ground, even during episodes of human impact and woodland clearance (see below). Episodes of intensified human activity seem to have impacted most on the populations of hazel and oak, with elm affected at some points, especially at the start of the Neolithic (*4040-3900 cal. BC*). The behaviour of *Fraxinus* (ash) suggests this fast growing and light demanding tree was favoured by the opening up of the woodland canopy during episodes of increased human activity (Caseldine and Hatton 1996).

The values for microcharcoal, an indicator of the frequency of burning in the landscape around the site (probably mainly from domestic fires, but potentially from natural burns), closely track these phases, with increased values associated with rises in pollen taxa indicating human activity. Microcharcoal falls noticeably during episodes of woodland recovery. The fluctuations in the LoI, MS and geochemical data provide additional information concerning the patterns of inwash and provenance of inorganic material into the Lough during the episodes of landscape disturbance. On the basis of these data, the most pronounced episodes of weathering at the catchment scale by far occurred during LC2, 4a, 7a and 7c, with the first presenting the clearest signal for the entire record.

The 8.2ka Event: Climatic forcing and vegetation change (LC-2)

The earlier Holocene landscape was dominated by deciduous woodland, consisting predominantly of hazel, oak and elm, with some birch and willow probably growing on the damper soils. Scots' pine was probably growing locally, despite the possibility of long-distance transport of this species' pollen (Pilcher *et al.* 1995, cf. Lageard *et al.* 1999). This limited representation is comparable with records from the east and midlands (e.g. Caseldine and Hatton 1996; Selby *et al.* 2005), although Scots' pine had become established locally at Kelly's Lough, Co. Wicklow (Leira *et al.* 2007) by 7450-7070 cal. BC (8220±50 BP, *ß-173463*).

The abrupt reduction in hazel and oak in LC-2 indicates significant changes in this woodland composition, also reflected by a pronounced fall in pollen concentrations. Hazel pollen production can be adversely affected by climatic shifts such as air frosts, drought or excessive precipitation levels (Tallantire 2002), while oak is also sensitive to early spring and autumn frosts (Giesecke *et al.* 2008). On the other hand, pine and birch are tolerant of low summer temperatures and can be rapid colonisers, given suitable conditions (Atkinson 1992; Richardson and Rundel 1998; Paus 2010). The expansion of pine and birch alongside the small increases in NAP, and the fluctuations in the geochemical, LoI and MS data, can be interpreted as the impact of climatic deterioration, possibly a shift to a more continental climate, with colder winters but also lower summer temperatures and a considerably lower annual thermal sum (cf. Huntley 2012).

The date range at Lough Cullin (*7120-6230 cal. BC* to *6350-5910 cal. BC*) correlates with climate anomalies in the Greenland ice-core records (Rasmussen *et al.* 2007; Thomas *et al.* 2007) between 8.5 and 7.9 kyr BP (Rohling and Pälike 2005). This climatic deterioration might have resulted from changes in the strength of the Atlantic meridional overturning circulation (cf. Alley *et al.* 1997; Alley and Ágústsdóttir 2005; Ellison *et al.* 2006; Hede *et al.* 2010), leading to colder and drier conditions in the North Atlantic region (Alley *et al.* 1997; Barber *et al.* 1999; Alley and Ágústsdóttir 2005; Wiersma and Renssen 2006). The clear palaeoenvironmental signature at Lough Cullin provides persuasive evidence for the impact of this climatic 'event' on the eastern as well as western seaboards of Ireland, with the chronology of the increase in Scots' pine overlapping with dendrochronological evidence for expansion in this tree after 6250 BC (Torbenson *et al.*, 2015).

Similar reductions in thermophilus taxa coincident with increases in cool-tolerant trees are exhibited in other Irish pollen records: Cooney Lough, County Sligo showed a marked reduction in pollen from hazel and oak, synchronous with expansion of pine and birch (Ghilardi and O'Connell 2012). Fluctuations in the frequency of juniper at An Loch Mór, Inis Oírr (Molloy and O'Connell 2004) and increased representations of pine at the expense of hazel are recorded during a period of erosion at Lough Maumeen, Connemara (Huang 2002).

The 'Elm Decline': Neolithic woodland clearance and agriculture

Mesolithic impacts on the environment have been identified in pollen records from the UK and Ireland (e.g. Smith 1970; Simmons and Innes 1996; Innes *et al.* 2003; Warren *et al.* 2014; Warren 2020), but there is little evidence for such 'disturbance events' in the Lough Cullin record, although the archaeological record indicates Mesolithic activity (Gleeson and Breen 2006a; 2006b; Wren 2006a; 2006b; Russell 2010). A continuous ribwort plantain curve and increased values for NAP (especially ruderal taxa) are evident from the Early Neolithic around *4040-3900 cal. BC,* and some *10-260 years* after the initial decline in elm at *4220-3980 cal. BC*. This may indicate the 'elm decline' was unrelated to human activity, although rising values for grass and trace values for anthropogenic indicators are coeval with reductions in this tree. However, this might equally reflect open environments resulting from the mortality of elm trees due to disease (Casedline and Fyfe 2006). The fluctuations in the geochemical data, LoI and MS are distinct, if not as pronounced as in LC-2, indicating the decline in elm was coeval with disturbance to local soils and inwash of minerogenic matter into the Lough. Other Irish records (O'Connell and Molloy 2001; Ghilardi and O'Connell 2013; Molloy *et al.* 2014; Kearney and Gearey 2020; McClatchie and Potito 2020), also indicate a 'gap' between the 'Elm Decline' and clear palynological evidence for human disturbance. Overall, this may refute an anthropogenic cause for the reduction in elm, although the chronological disparity could also reflect increased stimulation of arboreal pollen production resulting from openings to the woodland canopy (cf. Aaby 1986).

The Early Neolithic (LC-4a) is marked by the continuous presence of ribwort plantain from *4040-3900 cal. BC* until *3720-3540 cal. BC*, a duration of *220-450 years*. During this period, there was a substantial opening up of the woodland and expansion in open habitats, presumably relatively close to the lake, although this is considerably earlier than the estimated date (*3720-3680 cal. BC*) for the Neolithic 'house horizon' and the first cereal cultivation in Ireland (McSparron 2008; Cooney *et al.* 2011; McClatchie *et al.* 2014; Whitehouse *et al.* 2014; McLaughlin *et al.* 2016). Overall, the impact of Early Neolithic agriculture in Irish pollen records is rather variable (Connolly 1999; Crushell *et al.* 2008; O'Carroll 2012), perhaps reflecting the fact that Early Neolithic agriculture was spatially heterogeneous (Whitehouse *et al.* 2014) with varying levels of intensity, and the relative proximity of activity to sampling sites would further attenuate the signal.

Cereal-type pollen is recorded at *3900-3700 cal. BC,* an estimated *50-290 years* after the start of clearance and again from *3790-3580 cal. BC*. Palynological evidence from Newrath, south of Lough Cullin (Timpany 2009) also strongly suggests Neolithic arable agriculture at this time. The most reliable evidence is the presence of charred cereal grain in Neolithic archaeological contexts (e.g Hughes 2006; Monteith 2009; 2011; McKinstry 2010). The chronological model estimates farming continued for *220-450 years*, implying Early Neolithic farmers did not engage in shifting cultivation *contra* Iversen's (1941) *Landnam* model, but rather longer-term, fixed-plot agriculture (Whitehouse *et al.* 2014; McClatchie and Potito, 2020).

This phase of agriculture was followed by woodland regeneration and a decline in anthropogenic indicators from *3720-3540 cal. BC*. A similar pattern of re-afforestation is implied during the Middle Neolithic in other parts of Ireland (e.g. Ghilardi and O'Connell 2013; Molloy *et al.* 2014; Chique *et al.* 2017; Stolze and Monecke 2020). It has been suggested the Middle Neolithic saw a reduction in human activity overall (Whitehouse *et al.* 2014), rather than a shift in location, as reflected by the archaeological record: the number of confirmed Middle Neolithic archaeological sites in the region is substantially lower than in the preceding Early Neolithic, also in keeping with the archaeological evidence from across Ireland. This has also been linked to climatic change, dubbed the '5.2 ka event' (Roland *et al.* 2015), although the precise nature and timing of this remains unclear (Plunkett *et al.*, 2020).

Evidence for sustained human activity is subsequently absent until *2960-2525 cal. BC,* a period of woodland regeneration of estimated *660-1120 years*, followed by a renewal of arable and pastoral activity. The reappearance of agricultural activity during the Late Neolithic is indicated in other pollen records (Molloy and O'Connell 2004; Molloy *et al.* 2014; Stolze and Monecke 2020) whilst the archaeological record also suggests a limited Late Neolithic presence in south-east Ireland (Tierney 2005; Wren 2006b; Monteith 2011).

The reduction in Scots pine from *2620-2240 cal BC*, probably coincides with the beginnings of the 'Pine Decline' in the region. The decline of Scots pine has been well documented across much of Ireland, northern Scotland and England (e.g. Bennett 1984; Bridge *et al.* 1990; Gear and Huntley 1991; Pilcher *et al.* 1995; Lageard *et al.* 1999; Mighall *et al.* 2004), although recent studies have suggested the persistence of the taxa in certain regions (McGeever and Mitchell 2016; Sassoon *et al.* 2021). Numerous competing hypotheses have been proposed for the cause of this reduction, from climate (Bradshaw and Browne 1987; Mighall *et al.* 2004) to anthropogenic activity (Tipping *et al.* 2008), however Lough Cullin provides no conclusive evidence for the cause of this at the site.

Human activity from The Bronze Age to Early Medieval Period.

Relatively low levels of human activity are indicated during the Late Neolithic (LC-7a) through to the Chalcolithic/Early Bronze Age (LC-7b), followed by resurgence into the Middle Bronze Age (LC-7c), peaking in the Middle to Late Bronze Age (from *1500-1410 cal. BC* to *1275-1000 cal. BC*). Excursions in the geochemical data, especially Ca during LC-7c, followed by increases in Fe and associated peaks in MS towards the top of LC-8, support the picture that the Middle Bronze Age saw significant scrub/woodland clearance, farming and associated destabilisation of soils. Following this, human activity then seems to have decreased in two 'steps': an initial reduction, which may be described as a contraction, during the Late Bronze Age from *1275-1000 cal. BC* to *815-685 cal. BC* (LC-9) followed by a pronounced 'collapse' from *815-685 cal. BC* until *690-535 cal. BC* (LC-10), the Bronze Age to Iron Age transition. Human impact on the landscape seems to have almost completely ceased, quite abruptly in this latter period.

This pattern is paralleled by the changes in archaeological site distributions across this entire period (cf. Armit *et al.* 2013.; Becker *et al*. 2017); extensive landscape utilisation until the beginning of the Hallstatt plateau, followed by a marked contraction. This characteristic pattern can also be traced in the archaeology in the southeast (Eogan *et al*. 2015). Comparison with data from recently published Irish pollen records indicates a broadly coherent pattern during the Early to Middle Bronze Age of consistent and increasing woodland clearance and agriculture, followed by fluctuating human activity during the Late Bronze Age (Chique *et al.* 2017; Spencer *et al.* 2020; Stolze & Monecke, T. 2020). tt (2009) has previously drawn attention to a similar pattern, suggesting a link between increased archaeological visibility during the Late Bronze Age and palynological evidence for intensified pastoral activity, and indicating that the end of this period may have been characterised by consolidation of settlement and agriculture.

Climate change and human activity during Later Prehistory

It has long been suggested there is an apparent coincidence between the 'end' of the Bronze Age (ca. 1150-800/600 cal. BC) and evidence for climatic deterioration (wetter/colder conditions) across northwest Europe; the period known as the 'Sub-Boreal to Sub-Atlantic transition' or the '2.8 Ka event' (see Gearey *et al.*, 2020 for a recent review). Some scholars have suggested a direct causal link, with the onset of wetter/colder conditions, impacting directly on Bronze Age settlement and agriculture. However, Armit *et al.* (2014) have presented combined palaeodemographic (Armit *et al*. 2013) and hydroclimatic data (peatland Bog Surface Wetness/BSW records; Swindles *et al.* 2013) from Ireland, arguing a 'peak' in human activity *c.*1050 to 900 BC, was followed by a reduction to *c.*800 BC and a rapid 'collapse' to *c.*750 BC. The combined BSW data indicate climatic deterioration *c.*750-550 BC, which may suggest that this 'event' can be causally 'disconnected' from the 'end' of the Bronze Age, at least as indicated by the proxy demographic data.

There are few comparative palaeotemperature datasets for this period; although a recent chironomid-based reconstruction (expressed as mean July air temperature, referred to as Chironomid-inferred temperatures: C-ITs) is available from Lough Meenachrinna, Co. Donegal (Taylor *et al.* 2018). These data indicate C-ITs of 11.5℃ during the Early Bronze Age (*c.*1390 BC), rising into the Middle Bronze Age (*c.*1310-1100 BC) to peak at 13.5 ℃ (*c.*1260 BC), then falling to *c.*12 ℃ at the beginning of the Late Bronze Age (*c.*1150-960 BC). Slight increases in C-ITs to 12.8 °C are recorded from the end of the Bronze Age into the Iron Age (*c.*920-620 BC), later dropping to 11.4 ℃ (*c.*660-480 BC). The range of palaeotemperature fluctuations in this record are relatively small and their potential significance for human activity hard to assess (K. Taylor, pers.comm.)

However, 'events' in the Lough Cullin pollen record can be described as chronologically 'imbricated' with the palaeoclimatic 'events': a clear peak in human activity during the Middle Bronze Age, followed by contraction or consolidation during the Late Bronze Age and a pronounced fall into the Iron Age. The initial reduction (LC-9) also overlaps with the beginning of the palaeodemographic drop (Armit *et al.* 2014) and the subsequent 'collapse' (LC-10) with the postulated climatic deterioration in the BSW records (see also Plunkett *et al.*, 2020 who point to a gap in germination in the bog oak record between 751-713 BC and 709-668 BC). Correlations are hampered by the variable chronological precision of the different records; even with the improved chronological precision of the Cullin record, the ranges for the palynological 'events' are still 'smeared' over several centuries. Nevertheless, the chronological correspondence between the postulated climatic downturn (*c.*750 BC) in the BSW records and the contraction of human activity during the Bronze Age-Iron Age transition (*690-535 cal. BC*) at Lough Cullin can be noted; at the very least leaving open the possibility of a link between the two. Further analysis is also hampered by a general lack of detailed knowledge of the precise nature or severity of climatic changes, and an associated lack of clarity concerning pattern and process of social-cultural changes from Bronze to Iron Age (see Gearey *et al.*, 2020; Coyle-McClung and Plunkett, 2020 for further discussion).

Whatever the cause/s of the decline in anthropogenic activity during the transitional period between Bronze and Iron Ages, two 'steps' can be defined: a rapid recovery following the previous 'collapse' and marked expansion in woodland clearance and farming very soon afterwards, between *690-535 cal. BC* and *415-250 cal. BC* (LC-11). This was followed by another phase of woodland recovery from the latter date until *390-540 cal. AD* (LC-12). A marked period of woodland regeneration is a feature of many Irish pollen records during later prehistory, sometimes referred to as the 'Late Iron Age Lull' (Mitchell and Ryan 1997) although the reduction in activity dates to the Developed Iron Age at Lough Cullin. The timing of woodland regeneration and reduced human activity generally varies between records, from the final centuries BC to the early centuries AD (Chique *et al.* 2017). In some locations, human activity continued, albeit at fairly low levels, across the Late Iron Age (Figure 6). There are indications of drier/warmer conditions in Ireland from *c.*300 BC-400 AD (Coyle-McClung and Plunkett, 2020), corresponding broadly with the woodland regeneration phase (LC-11) in the Cullin record.

At Lough Cullin, human activity seems to have ceased almost completely until *cal. AD 390-540*, when there was a relatively abrupt resumption of the ribwort plantain curve, a steady rise in grass and reductions in hazel and oak (LC-13). Anthropogenic indicators demonstrate a marked increase and cereal pollen is recorded in almost all the samples across the zone, indicating a significant expansion of arable cultivation locally. In comparison to the sporadic record of cereal pollen from the rest of the sequence, the Early Medieval period saw the most extensive period of arable cultivation in the Lough pollen catchment. A steady rise in Fe and Ca towards the close of the zone, a peak in MS track rising NAP; the increasing LoI values is contrary to the evidence for increased mineral input, but may reflect increased eutrophication of the lake due to the input of organic material from intensified arable and pastoral farming; the record terminates at *cal. AD 780-1035* with increasing anthropogenic indicators and NAP and associated reductions in AP.

7. Conclusions

The Lough Cullin sequence provides a nuanced and detailed multi-proxy (pollen, loss-on-ignition, geochemistry and magnetic susceptibility) reconstruction of Holocene environmental and landscape change from *9050-8090 cal. BC* to *780-1035 cal. AD,* the Mesolithic to the Early Medieval Period; the provision of a high resolution radiocarbon chronology has allowed a comparatively high level of chronological precision for the later prehistoric period in particular, using Bayesian approaches permitting formal, robust estimates of the timing and duration of particular events, avoiding potentially misleading precision resulting from other approaches to age-depth modelling of palaeoenvironmental records. The data provide clear evidence for the impact of the '8.2 Kyr' BP climate event on the environment of the southeastern seaboard of Ireland. Certainly, on the basis of the geochemistry and magnetic susceptibility datasets, the 'signature' of the 8.2 'event' is very pronounced, which is interpreted as reflecting the impact of this colder/drier period across the entire catchment. Later alleged prehistoric climatic 'events' are largely obscured or overlain by human impact, reflecting woodland clearance, settlement and agriculture which began during the Early Neolithic, slackened during the Middle Neolithic before intensifying in the Middle-Late Bronze Age. The compilation of archaeological data has allowed a qualitative comparison of the palaeoenvironmental record with the spatially delimited evidence of human activity and taking account of the uncertainties associated with the interpretation of both records, broad correspondence in terms of implied intensities of human activity are indicated. A steady 'demise' of human activity during the Late Bronze Age-Iron Age is apparent, although there is no clear evidence to illuminate the cause/s of this, there is chronological correspondence with alleged national climatic deterioration around the mid-8th century BC. There is also unambiguous evidence for a reduction in human activity during the Iron Age until the Early Medieval period, providing further indication of the spatial and chronological variability of settlement and agriculture in Ireland across these periods. Despite ongoing archaeological and palaeoenvironmental investigation of the later prehistoric period in particular, uncertainties concerning data interpretation and variations in the chronological resolution, precision and robustness of different proxy climate records, hamper the formulation of mechanistic models linking environmental and cultural processes. The development of new methods and the generation of further, high resolution palaeoenvironmental records are one key to future progress, but this must include further research into archaeological data on regionally specific scales.

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LPAZ/Top Depth (m)	***Posterior density estimate (95.4% probability)***	***Posterior density estimate (68.2% probability)***	***Cultural period***	***Main pollen features***	***LoI***
LC13 2.15	*780-1035 cal. AD*	*810-940 cal. AD*	*Early Medieval*	Reductions in AP (*c.*55%) across zone, especially *Corylus* (*c.*20%), *Quercus* (*c.*10%) and *Alnus* (*c.*10%) towards top of zone. Increase in NAP (*c.*45%), especially Poaceae (*c.*20%), Cyperaceae (*c.*15%), *P. lanceolata* (*c.*4%) and *Rumex* (2%). *Cerealia*-type recorded across zone. Rise in *Pteridium* (*c.*10% TLP+S), Charcoal increases to peak midway through zone.	OM increasing *c.*40% at base to *c.*47% at top LPAZ. Average *c.*43%
LC12 2.36	*390-540 cal. AD*	*395-470 cal. AD*	*Late Iron Age*	Pronounced increase in AP (*c.*95%), especially *Corylus* (*c.*50%) and *Quercus* (*c.*30%), other arboreal taxa remaining steady. Falls in NAP predominantly Poaceae and Cyperaceae, *P. lanceolata* low and sporadic. Increase in charcoal towards top of zone.	OM increasing from *c.*36% to *c.*41% at top LPAZ. Average *c.*39%
LC11 2.64	*415-250 cal. BC*	*405-355 cal. BC*	*Iron Age*	Steady reduction in AP across zone (*c.*70%), primarily *Corylus* and following an initial increase*, Quercus*. NAP *i*ncrease, Poaceae rises (*c.*15%), also *P. lanceolata* (*c.*8%), Lactuceae (2%) and sporadic *Filipendula*. *Cerealia*-type recorded 2.65m. Charcoal low.	OM ranges *c.*34% at base to *c.*29% across LPAZ. Average *c.*31%
LC10 2.82	*690-535 cal. BC*	*630-555 cal. BC*	*Iron Age transition*	Increase in AP (*c.*90%), mainly *Corylus* (*c.*45%), other arboreal taxa remaining steady. Reductions in NAP, primarily Poaceae, *P. lanceolata* consistently present, at certain points higher values than the former. Charcoal low and sporadic.	OM increasing from *c.*33 to 37% across LPAZ. Average *c.*34%
LC9 2.925	*815-685 cal. BC*	*795-740 cal. BC*	*Late Bronze Age*	Both AP (between 70-85%) and NAP (30-15%) fluctuate cross the zone; former mainly due to changes in *Corylus* but *Quercus* also involved and the latter Poaceae; *P. lanceolata* remaining steady. Two *Cerealia*-type grains recorded at 3.08m, *Pteridium* peaks at *c.*15% and charcoal also shows increase above (3.04m).	OM ranges *c.*28% at base to *c.*35% at top of LPAZ. Average *c.*30%
LC8 3.14	*1275-1000 cal. BC*	*1225-1080 cal. BC*	*Middle Bronze Age*	Pronounced fall in AP (*c.*55%), especially *Corylus* (*c.*15%) and *Quercus* (*c.*10%) towards close of zone. Sharp increase in Poaceae and *P. lanceolata,* reaching highest values for diagram (*c.*28% and 7% respectively) also Cyperaceae (7%) and *Succisa*-type (2%), low values for Chenopodiaceae and *Filipendula*. Increase in *Pteridium aquilinum* (11% TLP+S) and Pteropsida monolete (indet.) (9% TLP+S) towards close of zone. Charcoal values very low.	OM increases from *c.*34 % to *c.*37% at 3.20m, decreasing to *c.*29% by top of LPAZ. Average *c.*32%
LC7c 3.34	*1500-1470 cal. BC (28.1%)* *1465-1410 cal. BC (67.3%)*	*1495-1480 cal. BC (17.5%)* *1455-1420 cal. BC (50.7%)*		AP remaining steady (*c.*80%), *Corylus* increasing (*c.*45%) towards top of zone. NAP increases initially (*c.*20%), mainly Poaceae and *P. lanceolata,* followed by reduction in former (*c.*10%). Charcoal increases slightly to peak at top of zone.	OM ranges *c.*34 to *c.*36% across LPAZ. Average *c.*35%
LC7b 3.56	*1880-1740 cal. BC*	*1875-1840 cal. BC (30.0%)* *1820-1800 cal. BC (14.1%)* *1780-1750 cal. BC (24.2%)*	*Chalcolithic & Early Bronze Age*	NAP remaining steady (15%); the latter mainly represented by Poaceae, low values for *P. lanceolata*. Charcoal remains low.	OM ranges from *c.*30% at base to *c.*40% at top LPAZ. Average *c.*33%

LC7a 3.90	*2620-2240 cal. BC*	*2505-2320 cal. BC*	*Late Neolithic*	*Ulmus* remains low, *Corylus* values fall mid-way to *c*.25%. Other trees at similar values to previous zone. Increased NAP (*c*.15%), a second continuous *P. lanceolata* curve (*c*.3%) from start of zone, Poaceae also increases, Asteraceae, Apiaceae, *Filipendula* and Ranunculaceae present. Single grain *Cerealia*-type (4.02m) alongside *Artemisia*-type. Pteropsida (monolete) indet. increases to 8% TLP+S. Charcoal values show very slight increase.	OM ranges *c*.33 to *c*.35% across LPAZ. Average *c*.33%
LC6 4.08	*2960-2525 cal. BC*	*2845-2630 cal. BC*	*Middle Neolithic II*	Steady reduction in *Ulmus* (*c*.2-3%), *Alnus* increases (*c*.25%) and *Salix* also present in slightly greater values (*c*.3%). NAP steady at *c*.7%, predominantly Cyperaceae, continuous Ranunculaceae, sporadic *Filipendula*, *P. lanceolata, Succisa*-type. Charcoal remains steady.	OM ranges *c*.35 to *c*.37% across LPAZ, dropping to *c*.30% at top. Average *c*.34%
LC5 4.38	*3355-3120 cal. BC*	*3275-3150 cal. BC*	*Middle Neolithic I*	AP values increase overall (*c*.95%), primarily *Corylus* (*c*.30%), *Quercus* (*c*.25%) and *Ulmus* (*c*.8%) and *Alnus* (*c*.20%). NAP values decline, only sporadic records of *P. lanceolata.* Slight increase in *Polypodium* (6% TLP+S). Charcoal remains steady.	OM ranges from *c*.35 to *c*.37% across LPAZ. Average *c*.36%
LC4c 4.71	*3685-3530 cal. BC*	*3650-3555 cal. BC*	*Early Neolithic II*	*Quercus* (*c*.25%) and *Ulmus* (*c*.4%) values recover, *Corylus* remaining *c*.30%. NAP values are reduced (*c*.5%) although a continuous but reduced curve for *P. lanceolata* (*c*.1% max) is exhibited, *Cerealia*-type pollen recorded (2 grains 4.77 and 1 grain 4.75m); other herbs similar to previous zone. Charcoal also remaining at similar levels.	OM ranges from *c*.31% at base to *c*.36% at the top of LPAZ. Average *c*.34%
LC4b 4.82	*3860-3650 cal. BC*	*3815-3710 cal. BC*	*Early Neolithic I*	*Quercus* (25 to 15%) and *Corylus* (40 to 30%) decreasing across zone; NAP increases to *c*.20%, predominantly Poaceae (10%), continuous presence of *P. lanceolata* (*c*.5%) and Ranunculaceae (*c*.1-2%), *Artemisia*-type, Asteraceae, *Rumex acetosella/acetosa, Filipendula* and *Urtica dioica* recorded at lower values. Single grain of *Cerealia*-type *(*4.85m). Charcoal increases at top of the zone.	OM ranges *c*.10% at 4.90m to *c*.31% at top of LPAZ. Average *c*.29%
LC4a 5.01	*4050-3960 cal. BC*	*4040-4010 cal. BC (25.8%)* *4005-3975 cal. BC (42.4%)*	*Late Mesolithic*	*Ulmus* values decrease at the start of zone (*c*.10% to *c*.3%) and thereafter remain very low; a temporary reduction in *Corylus* (*c*.25%), followed by recovery (*c*.40%). NAP values increase to *c*.10%, consisting of Poaceae (*c*.6%) and other herbs recorded include Asteraceae, Caryophyllaceae and *Plantago lanceolata.* Pteropsida (monolete) indet. increases to 9% TLP+S. Charcoal remains low.	OM ranges *c*.30 to *c*.25% at top of LPAZ. Average *c*.27%
LC3 5.09	*4320-4020 cal. BC*	*4225-4070 cal. BC*		*Corylus* recovers (*c*.40%), while *Alnus* increases steadily to a peak (*c*.25%), *Quercus* and *Ulmus* stable (20% and 10% respectively). The initiation of low but continuous *Ilex* curve is recorded at top of zone. NAP values remaining low. Slight if sporadic increases in charcoal.	OM ranges from *c*.29 to *c*.38%. Average *c*.34%
LC2 5.84	*6245-5575 cal. BC*	*6120-5780 cal. BC*	*Early Mesolithic*	Temporary reduction in both *Corylus* (*c*.30%) and *Quercus* (*c*.20%) corresponding with spikes in *Betula* (*c*.15%) and *Pinus* (*c*.20%), followed by recoveries in the former. *Alnus* increases abruptly at top of zone to *c*.15%. NAP remaining low (*c*.4%). Charcoal remaining very low.	OM ranges *c*.35 to *c*.33%. across LPAZ. Average *c*.34%

LC1 6.03	*7615-6500 cal. BC*	*7320-6745 cal. BC*	Dominated by AP, high values of *Corylus* (*c.*50%) and *Quercus* (*c.*30%), *Ulmus* (*c.*8%), *Pinus,* and *Betula* present (2-4%). A continuous but low presence of *Hedera helix* (2%) and *Salix* (1%). NAP values very low, traces of Poaceae, Cyperaceae and *Filipendula.* Charcoal very low.	OM ranges from *c.*35to *c.*40% across the LPAZ. Average *c.*37%

Lab Code	Dated Material	^{14}C Age (BP)	Depth (m)	$^{13}\delta$C ‰
UBA-22422	Fragment of willow branch	2526±32	1.78	-20.7
SUERC-70812	Organic sediment (humic fraction)	1141±32	2.19	-29.8
SUERC-70813	Organic sediment (humin fraction)	1198±29	2.19	-30.5
Statistically consistent measurements (T'=1.9; T' (5%)=3.8%; v=1). Weighted mean 1170±21				
Beta-423349	Organic sediment (humin fraction)	1420±30	2.29	-29.6
Beta-423350	Organic sediment (humic fraction)	1500±30	2.29	-29.9
Statistically consistent measurements (T'=3.6; T' (5%)=3.8%; v=1). Weighted mean 1460±22				
SUERC-70814	Organic sediment (humic fraction)	1661±27	2.37	-29.6
SUERC-70815	Organic sediment (humin fraction)	1635±29	2.37	-30.4
Statistically consistent measurements (T'=0.4; T' (5%)=3.8%; v=1). Weighted mean 1622±20				
Beta-426773	Organic sediment (humin fraction)	1910±30	2.45	−29.1
SUERC-70816	Organic sediment (humic fraction)	1959±29	2.49	-29.4
SUERC-70817	Organic sediment (humin fraction)	1996±29	2.49	-29.9
Statistically consistent measurements (T'=0.8; T' (5%)=3.8%; v=1). Weighted mean 1978±21				
SUERC-70821	Organic sediment (humic fraction)	2003±29	2.53	-29.2
SUERC-70822	Organic sediment (humin fraction)	2074±29	2.53	-29.7
Statistically consistent measurements (T'=3.0; T' (5%)=3.8%; v=1). Weighted mean 2039±21				
SUERC-72575	Organic sediment (humic fraction)	2114±29	2.55	-29.4
SUERC-72576	Organic sediment (humin fraction)	2135±29	2.55	-29.4
Statistically consistent measurements (T'=0.2; T' (5%)=3.8%; v=1). Weighted mean 2125±24				
Beta-426774	Organic sediment (humin fraction)	2150±30	2.60	-29.1
SUERC-72571	Organic sediment (humin fraction)	2181±33	2.61	-29.9
GU43402	Organic sediment (humic fraction)	FAILED	2.61	-
SUERC-70823	Organic sediment (humic fraction)	2250±29	2.65	-29.4
SUERC-70824	Organic sediment (humin fraction)	2336±29	2.65	-30.1
Statistically inconsistent measurements (T'=4.397; T' (5%) =3.8%; v=1).				
SUERC-70825	Organic sediment (humic fraction)	2328±29	2.71	-29.4
SUERC-70826	Organic sediment (humin fraction)	2436±26	2.71	-29.8
Statistically inconsistent measurements (T'=7.7; T' (5%) =3.8%; v=1)				
UBA-22423	Organic sediment (humin fraction)	2413±31	2.77	-25.0
SUERC-70827	Organic sediment (humic fraction)	2467±29	2.81	-29.3
SUERC-70831	Organic sediment (humin fraction)	2506±29	2.81	-29.6
Statistically consistent measurements (T'=1.0; T' (5%) =3.8%; v=1). Weighted mean 2489±20				
SUERC-70832	Organic sediment (humic fraction)	2446±27	2.915	-29.3
SUERC-70833	Organic sediment (humin fraction)	2514±29	2.915	-29.9
Statistically consistent measurements (T'=3.0; T' (5%) =3.8%; v=1). Weighted mean 2478±20				
Beta-426775	Organic sediment (humin fraction)	2620±30	2.94	-29.1
Beta-426776	Organic sediment (humin fraction)	2750±30	3.04	-28.9
SUERC-70834	Organic sediment (humic fraction)	2794±26	3.08	-28.9
SUERC-70835	Organic sediment (humin fraction)	2821±29	3.08	-29.7
Statistically consistent measurements (T'=0.5; T' (5%) =3.8%; v=1). Weighted mean 2806±20				
Beta-423351	Organic sediment (humic fraction)	3050±30	3.18	-28.8
Beta-423352	Organic sediment (humin fraction)	3020±30	3.18	-30.2
Statistically consistent measurements (T'=0.5; T' (5%) =3.8%; v=1). Weighted mean 3035±22				
SUERC-76326	Organic sediment (humic fraction)	3026±24	3.26	-29.6
SUERC-76666	Organic sediment (humin fraction)	3132±32	3.26	-29.8
Statistically inconsistent measurements (T'=7.0; T' (5%) =3.8%; v=1)				
SUERC-76327	Organic sediment (humic fraction),	3162±24	3.34	-29.3

SUERC-76328	Organic sediment (humin fraction)	3168±24	3.34	-28.5
Statistically consistent measurements (T'=0.0; T' (5%) =3.8%; v=1). Weighted mean 3165±17				
SUERC-76329	Organic sediment (humic fraction)	3469±24	3.56	-27.6
SUERC-76667	Organic sediment (humin fraction)	3473±32	3.56	-29.9
Statistically consistent measurements (T'=0.0; T' (5%) =3.8%; v=1). Weighted mean 3470±20				
UBA-22424	Organic sediment (humin fraction)	3800±36	3.79	-28.2
SUERC-70836	Organic sediment (humic fraction)	4459±29	4.31	-29.7
SUERC-70837	Organic sediment (humin fraction)	4520±27	4.31	-30.1
Statistically consistent measurements (T'=2.4; T'(5%) =3.8; v=1). Weighted mean 4459±29				
UBA-22425	Organic sediment (humin fraction)	4710±39	4.60	*
SUERC-70841	Organic sediment (humic fraction)	4755±29	4.69	-29.3
SUERC-70842	Organic sediment (humin fraction)	4795±26	4.69	-29.4
Statistically consistent measurements (T'=1.1; T'(5%) =3.8; v=1). Weighted mean 4777±20				
UBA-33721	Organic sediment (humin fraction)	5080±56	4.87	*
UBA-33722	Organic sediment (humin fraction)	5076±51	4.97	*
UBA-30917	Organic sediment (humin fraction)	5210±34	5.01	*
SUERC-70843	Organic sediment (humic fraction)	5675±27	5.34	-29.4
SUERC-70844	Organic sediment (humin fraction)	5788±26	5.34	-30.0
Statistically inconsistent measurements (T'=9.1; T'(5%) =3.8; v=1).				
UBA-22426	Organic sediment (humin fraction)	6154±47	5.46	*
UBA-30918	Organic sediment (humin fraction)	7358±37	5.91	*
UBA-22427	Organic sediment (humin fraction)	9057±48	6.21	*

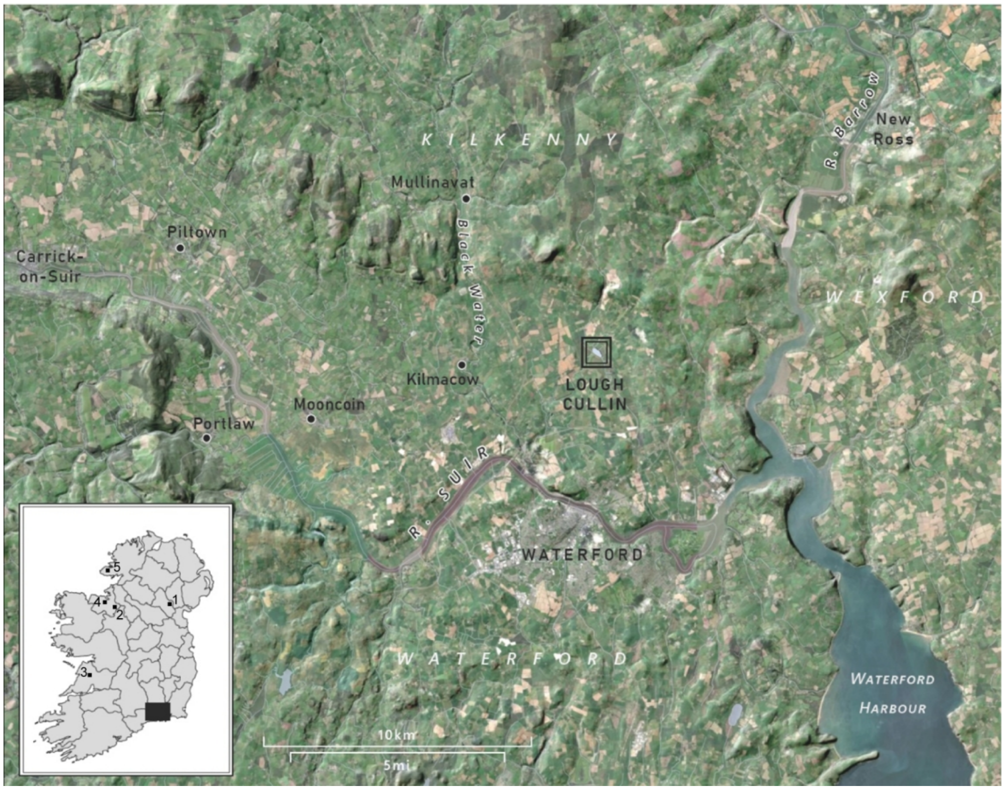

Figure 1 Location map of Lough Cullin. Inset map indicating the location of selected sites referenced in this paper. 1-Lough Muckno, 2-Lough Arrow, 3-Lough Inchiquin, 4-Lough Dargan & 5-Lough Meenachrinna.

404x316mm (118 x 118 DPI)

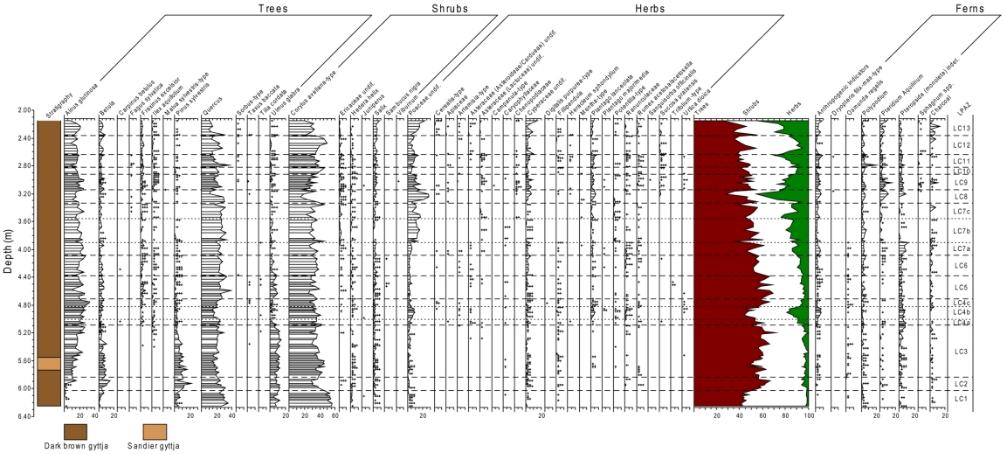

Figure 2 Pollen percentage diagram from Lough Cullin.

625x281mm (118 x 118 DPI)

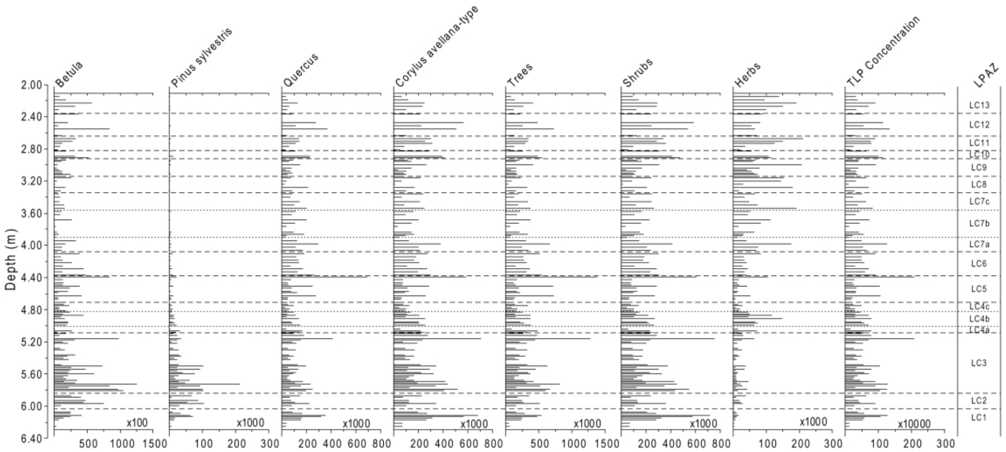

Figure 3 Selected taxa pollen concentration from Lough Cullin.

699x313mm (118 x 118 DPI)

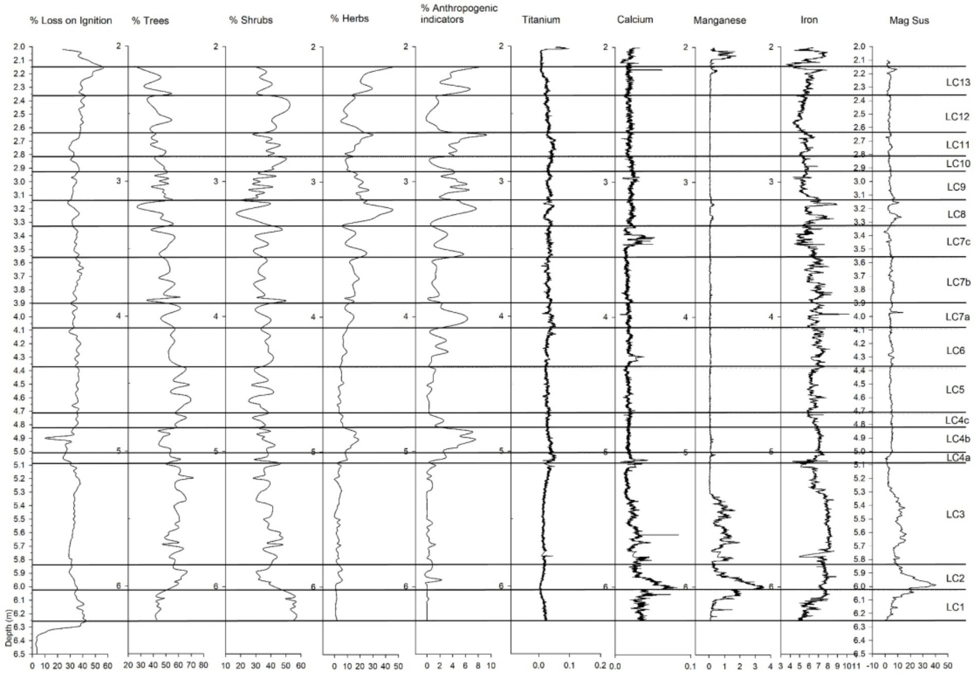

Figure 4 Loss-on-ignition (LoI), geochemistry and magnetic susceptibility (MS) diagram from Lough Cullin.

569x402mm (87 x 87 DPI)

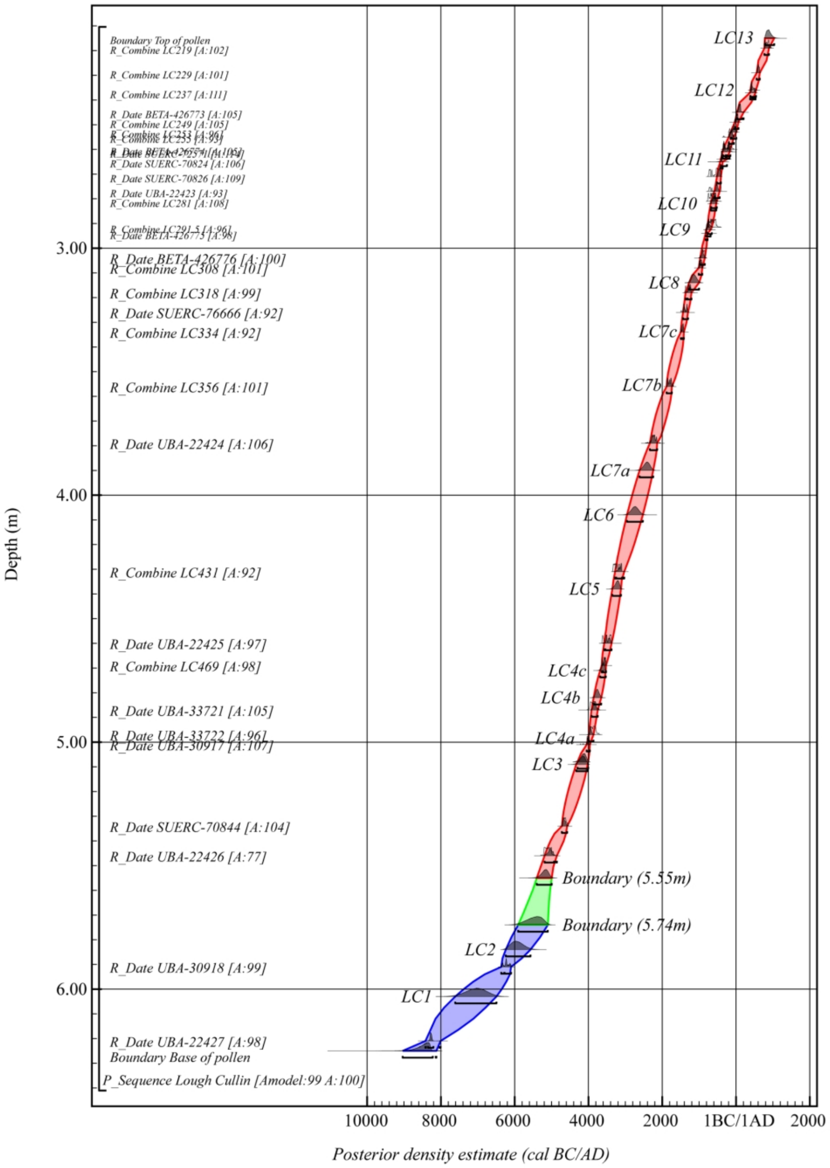

Figure 5 Bayesian age-model of the chronology of the sediment sequence at Lough Cullin (P_Sequence model (k=0.01-100) (Bronk Ramsey 2008). Coloured band showing the estimated date of sediment at the corresponding depth at 95.4% probability.

401x570mm (118 x 118 DPI)

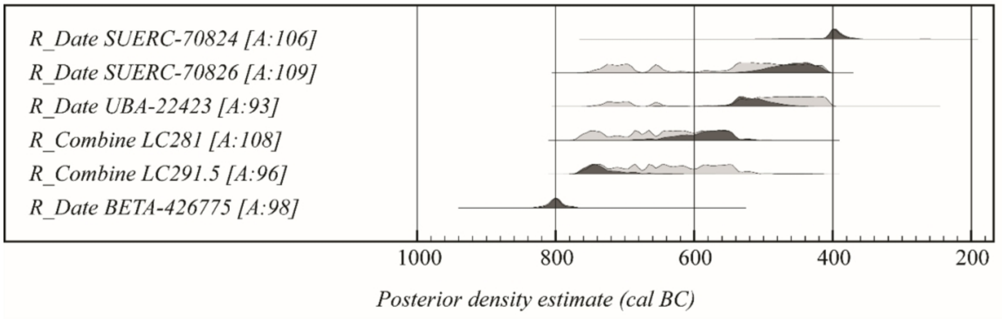

Figure 6 Unmodelled (light grey) and modelled (dark grey) dates across the ‘Hallstatt’ plateau. Modelled dates are derived from the Bayesian age-model shown in Figure 5.

400x127mm (87 x 87 DPI)